



PHD

Characterizing the relationship between energy and urban form using data, scaling and combined metrics

Osorio, Bruno Manuel

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CHARACTERIZING THE RELATIONSHIP BETWEEN ENERGY AND URBAN FORM USING DATA, SCALING AND COMBINED METRICS

submitted by

Bruno Manuel da Silva Osório

for the degree of Doctor of Philosophy

of the

University of Bath

Department of Architecture and Civil Engineering

November 2017

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Summary

A large proportion of energy demand comes from urban areas, mostly from buildings and transport, the use of which has impacts on climate and air quality through the emissions of greenhouse gases and other pollutants. To effectively mitigate these impacts, a better understanding of the relationship between energy and urban form variables is crucial. The link between energy and urban variables has been demonstrated before and it is recognised in many aspects of the cities, such as human behaviour and transport dynamics. This research goes forward by analysing the correlation and scaling between energy consumption and different land use typologies derived from urban form variables, as well as at other scales. The work is built on readily available datasets for England to guarantee the replicability of the methodology and ensure the reliability of the results. A combined energy use metric integrating buildings and commute transport produces helpful insights into energy consumption patterns and it is obtained at a large geographic scale. The identification of local scale consumption patterns is attractive to policymakers and planners by providing them detailed information to direct local-level policies. On the other hand, the derived land use typologies deliver new knowledge about the spatialisation of the urban system and to establish the link with the energy use. The results reveal that the relationship between energy and urban variables favours the application of compact city to reduce carbon-based energy consumption. This means that better energy efficiency is achieved by areas with higher population density. The analysis also shows that socio-economic variables have higher impact on energy consumption than physical variables. Moreover, differences at city scale and for the land use typologies are identified, demonstrating the importance of focusing the analysis according to the goal. In sum, the results from this work provide new insights about the relationship between energy and urban characteristics that can be used by policymakers and planners to outline more focused and detailed actions to mitigate energy use in England.

Keywords: Energy consumption – Urban form – Land use typology – Correlation – Scaling

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Research outputs

Throughout the 3-year research project, some parts of the thesis have been published or presented in conferences. These include:

1. the initial case study of the proposed energy use metric methodology in section 4.1 has been published in the *Sustainable Cities and Society* journal (Osório et al. 2017b);
2. the application of the energy use metric to three Local Authorities has been presented at the *21st International Conference on Urban Transport and the Environment* held in Valencia, Spain, and published in the respective conference proceedings (Osório et al. 2015);
3. a poster presentation of the full scale energy use metric for England at the *wholeSEM 3rd Annual Conference* held in Cambridge, UK (Osório et al. 2016);
4. an introduction to the analysis of the relationship between energy consumption and urban form metrics presented in section 5.3 has been published in the *Athens Journal of Sciences* journal (Osório et al. 2017a).

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Abbreviations and glossary

CO₂ – Carbon dioxide; colourless gas naturally found in Earth's atmosphere and used by many industries and in various applications

Compact city – urban planning concept or urban design typology promoting high residential density with mixed land uses

DECC – Department of Energy and Climate Change; British governmental agency that merged with the Department for Business, Innovation and Skills and renamed Department for Business, Energy and Industrial Strategy (DEBEIS)

EU – European Union; political and economic union of 28 countries located in Europe

GHG – Greenhouse gas; gas absorbing and emitting radiation within the thermal infrared range and essential in the greenhouse effect, including water vapor, carbon dioxide, methane, nitrous oxide, and ozone

GIS – Geographic Information Systems; system to store, manage, manipulate, analyse and present geographic information

GLUD – Generalized Land-Use Database; experimental statistics related to land use produced by the Department for Communities and Local Government in 2001 and 2005

K-means clustering – partitional clustering technique that splits n observations into k clusters based on the squared Euclidean distance between the cluster's mean and observations

LA – Local Authority; local government body in England

Land use development – process describing the function or purpose of the available land in a given area, region or country

Land use type (or typology) – function or purpose applied by humans to the available land in a given area, region or country

LUT – Land Use and Transportation or Land Use Transportation Interaction (LUTI); models describing the purpose of each piece of land in relation with the transport system

LSOA – Lower layer Super Output Area; statistics-purpose geographic area used by the ONS defined as covering between 1,000 and 3,000 people, and between 400 and 1,200 households

MJ – Megajoule; energy unit of measure

MSOA – Middle layer Super Output Area; statistics-purpose geographic area used by the ONS defined as covering between 5,000 and 15,000 people, and between 2,000 and 6,000 households

OD – Origin and Destination when talking about routes or trips

ONS – Office for National Statistics; UK's national statistical institute

OS – Ordnance Survey; UK's mapping agency

Outlier – value or data point on a graph or dataset that is much bigger or smaller than the next nearest observation

pc – per capita, i.e per individual/person

PCA – Principal component analysis; statistical technique to convert a set of observations of possibly correlated variables into a dataset linearly uncorrelated variables

Urban form – physical and socio-economic variables to describe the patterns, layouts, and structures of urban areas or spaces

Urban morphology – study of the spatial structure and character of urban areas by analysing patterns and the process of their formation and transformation

Urban sprawl – urban planning concept or urban design typology characterised by low-density and suburban development around the periphery of a city

Urban variable – quantity to describe the many features or characteristics of urban areas

Chapter 1

Introduction

The research presented here is focused on understanding the relationship between energy and urban form. The link between energy and urban form variables has been demonstrated by previous research (Cole & Neumayer 2004, Poumanyvong & Kaneko 2010, Martínez-Zarzoso & Maruotti 2011, Wang, Chen & Kubota 2016), but with a different scale, approach and results. Therefore, a better understanding of that relationship will provide new knowledge to planners and policymakers aiming at the reduction or mitigation of energy consumption based on carbon-intensive fuels. The motivations to implement those mitigation actions are broader, but essentially refer to the awareness of the numerous negative consequences of carbon-based energy demand, such as climate change, air pollution, decrease of quality of life (Hoornweg et al. 2011, Anderson et al. 2015) and many other environmental and socioeconomic problems.

The work in this thesis is built on readily available datasets for England to guarantee the replicability of the research and ensure the reliability of the results. The next sections present the overall scope of the research that helped to define the aims and objectives of the work.

1.1 Background

Economic development has been driven by industrialization and subsequent urbanisation, resulting in a wide and continuous growth of population, now mainly living in cities and general urban spaces (Fassmann et al. 2005, Madlener & Sunak 2011, Reinhart & Davila 2016). This growth has caused an increase of global energy demand (Creutzig et al.

2015, Komal & Abbas 2015), much of that final energy being used in cities and other urban areas (Pacione 2005, Dhakal 2009, Hoornweg et al. 2011). Considering that energy supply is largely obtained from fossil fuels (IEA 2011, Madlener & Sunak 2011, Anderson et al. 2015), cities are a significant source of CO₂ and other greenhouse gases (GHG) emissions (Pacione 2005, Dhakal 2009, Anderson et al. 2015). These emissions result in a large number of negative consequences, from global warming and the rising of urban temperatures recognizable by the urban heat island effect that have a direct impact on health and welfare (Buechley et al. 1972, Changnon et al. 1996, Prashad 2014). Tackling these issues presumes the outline and implementation of strategies and policies that reduce carbon-based energy dependency of cities and suggest alternatives to the use of finite and highly polluting energy resources (WI 2017).

As the ongoing urbanisation is expected to continue at high rate (UN-DESA 2014, Reinhart & Davila 2016), generating an ever increasing urban energy demand, immediate actions are required in the following years to secure a more sustainable urban environment (Pacione 2005, Davis & Caldeira 2010, Hoornweg et al. 2011) and change the carbon-based society. The design of those actions and policies begins by assessing the current patterns of energy consumption, the identification of land use typologies devised from urban form variables and the understanding of the relationship between the two. However, it is important to be aware that any strategies and policies should be established considering the overall framework of global and national urban planning, its challenges and opportunities to seek a more sustainable development. Although the reduction of carbon-based energy demand and the understanding of its close association with urban form or land use are not always demonstrated in the urban planning practice (Bai et al. 2017), a more sustainable development planning should also be supported by a better knowledge about their relationship in such complex systems as urban areas and cities, an understanding that is the main focus of this thesis.

The decrease of energy demand is recognised as one of the many challenges that sustainable urban planning needs to address to ensure that cities and human settlements are for everyone and to optimize the spatial dimension of urban form (UN-Habitat III 2016). Globally, the United Nation's New Urban Agenda (UN-Habitat III 2016) seeks to set up a urban paradigm shift to arrive at a sustainable development, though critics mention the lack of novelty compared with previous agendas, such as Habitat I or II, since actual change in urban planning depends much of government competence (Satterthwaite 2016) and their compromise in achieving goals. The current government planning policy for England – the National Planning Policy Framework (NPPF) (DCLG 2012) – lays down the main principles of a planning framework seeking a three-dimensional sustainable development: economic,

social and environmental. Those principles provide an essential structure for a better urban, local and neighbourhood planning system, including the mitigation of climate change and the reduction of energy consumption.

1.1.1 Energy consumption, carbon and GHG emissions

Energy is converted to useful work, heat and waste by many individual components (Keirstead & Shah 2013) that interact and compose urban spaces or areas. Buildings and transportation are considered the main energy demanding vectors in cities and urban areas (Steemers 2003, Banister et al. 1997, Hickman & Banister 2014), the first consisting mainly of electricity, gas and heating consumption, and the second arising from the burning of petroleum products.

The buildings sector is more homogeneous, consisting in residential and non-residential stock. In 2009, 75% of the building stock for the set comprising the European Union of 27 member states (EU-27), Norway and Switzerland covered residential buildings, which already accounted for 68% of the total final energy use in buildings (BPIE 2011). In 2014, residential buildings alone accounted for more than 24.8% of the overall total energy consumption (EC 2016), making it an important energy consuming vector. Additionally, the energy consumption of the complex non-residential buildings sub-sector has also increased over the last 20 years (electricity consumption raised 74%) (BPIE 2011). These trends are expected to continue if action is not taken to improve the performance of buildings.

In the UK, about 31% of the total energy consumption referred to residential buildings and more than 38% are related to industry and non-residential buildings in 2014 (DBEIS 2017*b*). However, the split of consumption between the two is different: in 2014, about 91% of the expenditure of residential buildings refers to electricity (24%) and gas (67%) (DBEIS 2017*b*). In contrast, approximately 20% of the consumption of industry and non-residential buildings arises from petroleum products, and the proportion of electricity and gas is similar: around 33% in 2014 (DBEIS 2017*b*). Moreover, the energy expenditure of industry and non-residential buildings is about 21% more than the consumption of residential buildings (DBEIS 2017*b*), and non-domestic buildings explain more than 15% of the total UK's CO₂ emissions (Adeyeye et al. 2007). Nonetheless, the total consumption of both residential and non-residential buildings has decreased between 20 and 21% since 2005 (DBEIS 2017*b*), which may indicate that some of the measures that have been taken related to energy efficiency are producing results. Yet, the consumption in the UK is still about 86,629 thousand tonnes of oil equivalent (ktoe) (DBEIS 2017*b*) with only 7% supplied by renewable sources in opposition to, for example, Portugal (27%), Germany (13%) or France (14%)

(EC 2016).

The transport sector is very heterogeneous because it includes different modes of travel, each of which displaying dissimilar energy use. However, the reliance of the sector on petroleum products makes it vulnerable to oil supply disruptions (Wang 2008) and a large source of carbon emissions and other GHG, and so makes this the energy vector requiring more urgent actions. For example, in 2014, more than 330 ktoe of the transport's energy consumption within the EU-28 resulted from petroleum products (EC 2016), widely known for their highly polluting effects. In the same year, transport accounted for more than 33.2% of the total energy consumption (or 352.9 Mtoe – million tonnes of oil equivalent) (EC 2016). In the same way as with buildings, the expansion of the energy demand by transport seems not to slow down, mostly in energy-hungry subsectors as aviation and road transport, contributing to the increase of GHG emissions, urban pollution and anthropogenic global warming (Fuglestad et al. 2008).

The scenario in the UK is not much different: almost 100% of the energy consumption of transport originates from petroleum products, mostly in the road transport sub-sector, in 2014 (DBEIS 2017b). Transport itself represents about 30% of the total energy consumption in the UK, and is the only sector to have expanded its proportion in the total UK's expenditure since 2005 (DBEIS 2017b). Although a decrease of about 4% has been observed in transport's consumption (DBEIS 2017b), that reduction is not significant if compared with buildings (values above 20%). Therefore, transport is a significant sector in urgent need of strategies to reduce and mitigate the total energy consumption, mostly due to its dependency on petrol and diesel (depending on refined oil products) which are a significant source of carbon and other GHG emissions.

Cities and urban areas only cover 2% of the world's surface, but explain about 70% of energy-related CO₂ emissions and 75% of world's consumption of resources (Madlener & Sunak 2011). In 2014, CO₂ emissions in the EU-28 totalled 3603 MtCO₂ (million tonnes of CO₂), more than 89% related to fuel combustion activities (EC 2016). This represents 7108 kg CO₂ per capita, but still only 79.7% of 1995 values (EC 2016). For the UK, the figure is slightly higher – 7220 kg CO₂ per capita –, though smaller than countries like Germany (10117 kg CO₂ per capita) or Lithuania (20142 kg CO₂ per capita) (EC 2016). However, the total CO₂ emissions for the UK in 2014 is 464 MtCO₂, the second highest in the EU-28 (after Germany) and describing about 13% of the total (EC 2016). Analysing the overall GHG emissions in the UK, the transport and residential buildings categories account for almost 49% of the final user total (DBEIS 2017b). The GHG emissions from road transport in 2014 explain more than 57% of the total transport (DBEIS 2017b), and it is estimated that commute transport represents about 3% of the total UK's GHG emissions

(Lovelace 2014).

On the whole, the amount of energy use and related carbon and GHG emissions that most countries experience cannot be maintained for much time at the expenses of the depletion of resources, climate change and many other negative consequences. Urgent and effective actions are needed to guarantee a sustainable society for future generations. Nevertheless, although this is recognised by many governments and actors, delaying changes and proposing half-measures seems not to ensure the success of policy strategies. Yet, researchers' mission is to always propose different strategies based on the available information.

1.1.2 Climate change

Human-induced climate change is recognised by most current research and its impacts are largely studied (Hughes 2000, Hardy 2003, Pachauri, Rajendra K. and Allen, Myles R. and Barros, Vicente R. and Broome, John and Cramer, Wolfgang and Christ, Renate and Church, John A. and Clarke, Leon and Dahe, Qin and Dasgupta, Purnamita and others 2015). Moreover, the anthropogenic changes of the Earth's atmosphere due to, mostly, the combustion of fossil fuels during the last century (and continuing to the current one) resulted in the increase of temperature, decline of many ecosystems, and extreme weather phenomena (Crowley 2000, Lovelace 2014, Easterling et al. 2000). These changes and related consequences are directly associated with the increase of carbon dioxide (CO₂) and other gases concentration in the atmosphere (Solomon et al. 2009, Anderson et al. 2015) that produced the so called greenhouse effect. The effects are even more significant because the increase of the concentration of carbon dioxide is seen as irreversible for many centuries (Solomon et al. 2009, Cai et al. 2013).

The growth of CO₂ and other GHG emissions was mainly caused by the increase of energy demand since the Industrial Revolution, and currently most of the carbon-related energy demand is associated with cities and urban areas (Keirstead & Shah 2011, Dhakal 2009, Anderson et al. 2015). This demand results from the different characteristics of the cities – form, function, energy supply system, life cycle of materials and lifestyles of the population (Hoornweg et al. 2011, Keirstead & Shah 2011) – that influence their energy efficiency (Rossi et al. 2016, Poruschi & Ambrey 2016, Santamouris 2013). The urban environment layout assumes an important role in that efficiency and its improvement, thus requiring stronger actions to tackle climate change and its effects.

The main energy demanding vectors in cities and urban areas are buildings and transport, and so about 67% of global primary energy demand and 70% to 80% of energy-related

GHG emissions are originated from cities (Keirstead & Shah 2011, Hoornweg et al. 2011, Steemers 2003, Hickman & Banister 2014). Therefore, the ongoing debate on the mitigation of human-produced climate change is essentially directed to reduce energy consumption and the respective CO₂ and other GHG emissions by those two vectors. At the present time, climate change is also putting pressure on the economic and social development, mostly of low- and middle-income countries (Hoornweg et al. 2011), urging the design of effective strategies to reduce the many negative impacts. Because the work presented here looks into the relationship established between energy consumption and the physical and socioeconomic variables of urban spaces, the research concerns also climate change.

The acknowledgment of climate change has introduced environmental concerns into the political debate. The search for a more sustainable development of the world and the establishment of an environmental political agenda began, essentially, with the Brundtland Report (Brundtland et al. 1987) and the Rio Conference (Panjabi 1997). These have been followed by other important conferences, summits and meetings, mostly under the framework and organized by the United Nations. However, only a few binding agreements have been made to tackle the problem, the most important being the Kyoto Protocol (Grubb et al. 1999) and, recently, the Paris Agreement (UNFCCC 2015, Dimitrov 2016) that followed the 2015 United Nations Climate Change Conference (UNCCC). Other agreements failed to enter into force, as for example the Earth Summit in 2002, the Bali Road Map that followed the 2007 UNCCC and the 2009 UNCCC, mainly because some of the largest GHG emissions countries, notably the United States, China, India and Russia, did not ratify them.

The UK, as part of the EU (at least until Brexit comes into full effect), has adopted many of the EU's climate-related initiatives and strategies within the European Climate Change Programme. This seeks to promote the use of renewable energy sources and mitigate CO₂ emissions by the transport sector. From the key targets of the difference policies, the EU proposes to (i) cut by 20% of GHG emissions (from 1990 levels) by 2020 – a cut that should reach 40% by 2030 –, (ii) increase energy efficiency by 20% (27% in 2030) and (iii) increase the energy production by renewable sources. A 2016 report of the European Energy Agency describes an overall decrease of 24% GHG emissions for the EU-28, although the emissions from road transport increased by 17% (EEA 2016). This information reveals that much work is still to be done to reach a sustainable development. Furthermore, the withdrawal from the European Union by the UK may put in danger some of the climate change mitigation goals rectified by the UK as part of the EU. Incorporating many of the EU laws into the UK domestic law seems to be a way of avoiding that possibility, but at the moment it is not clear if that will happen. Therefore, academics and researchers can only

make pressure by making available manifold studies that demonstrate the importance of continuing to implement actions to reduce carbon-related energy consumption. Accordingly, the work presented here aims also at providing new insights of the relation between energy consumption and urban characteristics at a large scale of analysis to equip policymakers and planners with better tools and information.

1.1.3 Planning, boundaries and energy

Tackling the energy problem and the need to reduce demand derived from fossil fuels has to be considered within the global, national and local urban planning framework, as cities and urban areas are complex systems where different interactions and dynamics are observed (Hillier & Vaughan 2007, Batty 2005). As structures developed by human beings, each urban area and city presents a diversity of economic, social, historical, topographical, environmental and political patterns (Goh et al. 2016) that influence (and are affected by) the mentioned dynamics. This includes many aspects of the cities, such as land use, built environment, general infrastructure, transportation networks, and thus also energy consumption. Therefore, the energy problem is interconnected with other urban systems in a critical cause-and-effect loop, since it's a driving force of modern development (Poggi et al. 2017). Designing any energy use mitigation actions must recognise and should integrate information related to the other urban systems, as well as be aware of past and current urban plans and processes.

The United Nations (UN) has been one of the major worldwide actors concerned with the many problems and challenges found in cities and urban areas. In that way, by working towards a more sustainable development, three main documents have been produced containing goals and guidelines for the following years. The last of these documents – the New Urban Agenda – resulted from the Habitat III conference held in Quito, Ecuador, in 2016, and it is a compromise of the UN member states for a long-term and integrated urban and territorial planning (UN-Habitat III 2016). Representing a urban paradigm shift to lay down principles for planning, construction, development, management and improvement of cities and urban areas, covers both national and local scales, as well as legislation and regulations, urban planning and design, finance and implementation of strategies. As for the energy topic, it is recognised the importance of urban form, infrastructure and building design as the main factors to achieve better energy efficiency. Consequently, more energy-efficient buildings and construction modes are endorsed within a universal planning framework seeking to reduce the impact of cities and urban areas on the environment. It is believed that better energy efficiency will allow a reduction of carbon and other GHG emissions towards

more sustainable urban areas. The New Urban Agenda also addresses the concerns about climate change by promoting adaptation and mitigation measures at different scales, but also encouraging a spatial development that prevents urban sprawl, usually associated with energy inefficiency. Overall, the document aims at a urban planning that ensures a better social, economic, financial and environmental quality of life in cities and general urban areas.

In England, the government produced a document – the National Planning Policy Framework (NPPF) –, available from 2012, to set out a framework for a planning system to achieve a sustainable development (DCLG 2012). This sustainable development is not exclusive of urban areas and the NPPF acts as a guidance for local planning authorities, i.e. local councils, and decision-makers. It is recognised the importance of a better land use planning and management to arrive at a sustainable development by giving power of decision to local people to lay down local and neighbourhood plans that improve the locations where people live. From the different principles mentioned in NPPF, the majority is common to UN's New Urban Agenda, specifically related to infrastructure, transport, climate change and housing needs.

The NPPF points out the need to seek high quality design of buildings and infrastructures to support better energy efficiency and transition to a low carbon society, as well as provide affordable, sufficient and sustainable housing that reflects local demand. The challenges of climate change are not only addressed through better building design, but it is also encouraged the reuse of previously developed land (brownfields), the use of renewable resources and the protection of green belt areas. These green belt areas are of crucial importance to prevent urban sprawl development, acknowledged as energy inefficient, and to safeguard the countryside from encroachment by neighbouring urban areas. Therefore, the climate change mitigation strategies are the main planning actions towards an energy policy in the NPPF. This can also be found for the transport policies regarding sustainable development, by the means of promoting the use of public transport and more environment-friendly transport modes, such as walking and cycling, to support the reduction of GHG emissions and reduce congestion in cities and urban areas. In conclusion, NPPF follows a similar approach to the New Urban Agenda by acting as a key document to achieve a sustainable development and proposing a set of actions and strategies to reach that goal. Both documents seems to respond to some concerns that urban planning and management practice not always reflects the evident link between urban form or land use and urban microclimate, for which a integrated systems approach is best suited (Bai et al. 2017, Moghaddam et al. 2014).

From an energy policy and planning point of view, it is also important to recognise that en-

ergy use and demand cannot be limited by administrative boundaries, mostly because these do not entirely describe city and urban limits. Identifying urban boundaries and working across administrative boundaries is essential to implement carbon-based energy reduction actions (Satterthwaite 2016, Inouye et al. 2015). Arbitrary boundaries such as administrative boundaries do not satisfactorily distinguish between urban and rural areas (Masucci et al. 2015, Satterthwaite 2008), which poses a problem for the success of energy reduction strategies. In the NPPF it is recommended the cooperation between local authorities for cross boundary developments so that sustainability is ensured. However, though NPPF is designed for local scale planning, it is not specified how that cooperation should take place. The boundaries issue is not directly mentioned on the New Urban Agenda, although a positive association between urban, peri-urban and rural areas on economic, social and environmental aspects is supported. In this thesis, a large scale geographic unit is used to prevent defining urban boundaries but also ensure a replicable methodology to estimate energy consumption (see sections 1.2.1 and 4.1.1.2 for more details).

1.2 The relationship between energy and urban form

The physical and sociodemographic characteristics of cities and urban areas have significant impacts on their internal and external dynamics. These dynamics include social, economic, cultural, psychological, political and many other aspects of cities that influence the quality of life, gender equality, health, education, etc. of the urban populations and the environment, sustainability, development, spatial organisation, governance and others of urban spaces (Corburn 2017, Santamouris 2013, Feng et al. 2013, Arcaute et al. 2015, Louf & Barthelemy 2014a, Portugali et al. 2012, Czamanski & Broitman 2016). Therefore, energy demand is also influenced by those characteristics (Bai et al. 2017, UN-Habitat III 2016) which are important to understand in order to reduce and mitigate carbon-based energy consumption and related GHG emissions. In this research, the relationship between energy and urban characteristics is studied to provide new knowledge that may contribute to the reduction and mitigation of that consumption.

Previous research has been published analysing, for example, the relationship between energy consumption and urbanization (Zhang & Lin 2012, Al-mulali et al. 2013, Wang, Wu, Zeng & Wu 2016, Wang, Chen & Kubota 2016). On transport energy consumption, and since the seminal work by Newman & Kenworthy (Newman & Kenworthy 1989), many studies examined, for example, the relation between household travel behaviour and that consumption (Jones et al. 1983, Dieleman et al. 2002, Handy 1996, Boarnet & Crane 2001). Research has acknowledged the effect of land use and urban form on travel be-

haviour (Kockelman 1997, Pan et al. 2009, Liu & Shen 2011, Heinen et al. 2015) and, thus, on the energy consumption of transport. The link between transport fuel consumption and population density (Newman & Kenworthy 1989, Brownstone & Golob 2009) has also been established, but there are no conclusive findings on the relationship between urban characteristics and overall energy consumption (Mindali et al. 2004, Makido et al. 2012).

Most of the previous research has used lower geographical resolutions to study that relationship (Mindali et al. 2004, Song & Knaap 2004, Schwarz 2010, Liu & Shen 2011), or has examined only a few boroughs/residential areas of large cities (Dieleman et al. 2002, Holden & Norland 2005, Ewing & Rong 2008). High resolution studies mainly focus on transport energy consumption and travel behaviour (Handy et al. 2005, Næss 2012, Shim et al. 2006). However, long-term planning to reduce and mitigate energy consumption in urban areas demands also for the analysis of the consumption of buildings, i.e. residential and non-residential buildings. Accordingly, an integrated approach of the energy consumption of buildings and transport and the use of high resolution analysis benefits planning, policymaking and the improvement of urban energy efficiency (Moghaddam et al. 2014, Østergaard & Sperling 2014, Pasimeni et al. 2014).

Urban form variables are often used to describe the aforementioned physical and sociodemographic characteristics of cities. In the present work, a large dataset of urban form variables is used to understand its relationship with energy consumption. To show how urban form influences energy (Larivière & Lafrance 1999, Creutzig et al. 2015, Mindali et al. 2004, Poumanyong & Kaneko 2010), this research is split in three major stages: (i) design of a new, simple energy use metric; (ii) identification of main land use typologies in England based on urban form variables; (iii) understanding the relationship energy and urban form at different scales by looking for correlations and scaling laws between both sets of information. The following sections outline the essential groundwork of these three stages, later detailed in the respective methodology chapter (see sections 4.1 and 4.2). Fundamentally, the study of the relationship between energy and urban form seeks to aid urban planners both designing new cities and redesigning the existing ones to achieve better energy efficiency and tackle the current challenge of reducing carbon-based energy to prevent their consequences.

1.2.1 Energy estimation

Cities and general urban areas account for between 67% and 76% of global energy consumption (Creutzig et al. 2015) and similar quantity of GHG emissions (Hoornweg et al. 2011). Strategies seeking to reduce or mitigate that consumption should begin by esti-

inating urban energy consumption. However, estimating urban energy is not an easy task due to the heterogeneous nature of cities that encompass diverse sectors and sub-sectors for which it is difficult to obtain information. Moreover, many approaches consider these sectors and sub-sectors separately because of the distinct data collecting procedures. This raises difficulties in comparing consumption and outlining actions that cover the whole urban system.

Buildings and the transport sector are considered the main energy consuming vectors in cities and urban areas (Banister et al. 1997). Yet, quantifying the actual energy consumption values of every urban component (i.e. each building and vehicle) is virtually unrealistic. Therefore, estimates are produced to provide planners and policymakers information about energy demand to support energy-related strategies. Different methods are used to generate those estimates, though no definitive solution has been found, moreover when collecting data for large regions. A common approach is the use of models, for both buildings and transport (Brand et al. 2012, Crawley et al. 2000, Feng et al. 2013, Fumo 2014, Gerber 2014, Heiple & Sailor 2008, Howard et al. 2012, Travesset-Baro et al. 2016, Yin et al. 2015), that try to reproduce the complexity the real world.

Essentially, approaches can be split into bottom-up and top-down methods: the first is preferred for urban scale studies; the second more suitable for large regions. Nevertheless, both approaches face challenges in generating satisfactory (or least complete) information, although no ideal approach is found in the literature. For example, the use of models may provide very detailed energy use estimates, but their typical complexity and prerequisite of large volumes of input data that are not generally available for the majority of cities or urban areas, restrict their application to high resolution areas. In this work, a simple and replicable approach is used based on a large geographic scale of analysis to set a better framework to implement actions that can reduce energy use.

The collection of energy consumption information in most developed countries is carried out by official government departments. In the UK, the Department of Energy & Climate Change (DECC)¹ is the principal government bureau publishing energy-related data, although other departments also compile information, mostly on transport fuel expenditure. However, in addition to this statistical information, surveyed data is also found in some studies (Banister 1996, Dieleman et al. 2002, Chen et al. 2011), as well as the re-use of previous datasets (Chen et al. 2011, Mindali et al. 2004, Banister et al. 1997). In this thesis, only data published by official government institutions is used, as these are deemed reliable sources. The use of readily available information is also regarded as highly relevant

to politicians and planners designing long-term strategies (Lovelace 2014).

In this research, a combined new, simple energy use metric is introduced (see section 4.1). The proposed metric benefits of the (but not restricted to): (i) integration of both buildings and transport energy consumption; (ii) use of large scale geographic units – Lower layer Super Output Areas (LSOAs)² – to avert defining city/urban boundaries; (iii) simplicity and replicability of the procedure; (iv) use of official available information considered trustworthy references. Therefore, the approach is a new, simple, replicable alternative method to estimate energy to provide planners and policymakers with additional information on urban energy. Furthermore, the energy use metric is aimed to the end-user and local councils and so it is assumed that the operational energy of buildings and commute transport energy are the main variables over which authorities and urban planners have more direct control through policies seeking to reduce energy use. The inclusion of, for example, buildings embodied energy would not provide new information to local authorities about the existing building stock, at which the policies are directed. At the same time, the use of the fine-grain detail LSOA units enables local governments to have a better understanding of the energy internal dynamics of cities and urbanised areas, in addition to the regional dynamics and between cities.

1.2.2 Urban form and land use

Urban form refers to the physical and socio-economic characteristics of urban areas, which have an impact on the many human activities developed in cities, as economic, environmental, social and technological processes (Tsai 2005, Schwarz 2010, Creutzig et al. 2015). Consequently, energy consumption should also be influenced by urban form configuration. However, current research hasn't found definitive conclusions about that influence. This thesis aspires to develop and expand the knowledge about that influence by examining the relationship at a large geographical scale.

Defining urban form is not an easy task, as definitions vary in the literature (Kasanko et al. 2006, Tsai 2005, Schwarz 2010). Predominantly, urban form describes the spatial structure of cities based on landscape metrics and socio-economic indicators (Lowry & Lowry 2014, Schneider & Woodcock 2008, Frenkel & Ashkenazi 2008). The landscape variables are related to shape and size of the urban areas; the socio-economic variables refer to the human

¹The Department for Business, Energy & Industrial Strategy (DBEIS) since July, 2016. Considering that the majority of the information used in this thesis was still published under DECC's name, this denomination was kept.

²Considering that the case study in this thesis is the whole England, the total 32,844 LSOA units are used.

and social aspects of cities (Huang et al. 2007, Lowry & Lowry 2014, Schirmer & Axhausen 2015). The analysis of these variables seeks to understand the internal processes of urban areas. This can be used to provide planners with better knowledge about development. Accordingly, quantifying urban form is often motivated to assess policies aimed at urban development (Lowry & Lowry 2014).

The introduction of sustainability to urban development and policy resulted in a link between urban form and sustainable development. Within this sustainable development, energy consumption is one of the main aspects in urban areas, specifically the encouragement of energy efficiency. This puts in confrontation two keys urban development theories: that of compact city and urban sprawl (Mörtberg et al. 2017) (more details in Chapter 2). Much research has been published on the subject (Frenkel & Ashkenazi 2008, Breheny 1995, Burton 2000, Dieleman & Wegener 2004, Ewing 2008, Chen et al. 2008). Though transport-focused studies mostly argue in favour of compact city principles – higher densities result in lower energy consumption and bring better energy efficiency –, definitive conclusions are yet to be found on the relation between energy and urban form (Makido et al. 2012). In this thesis, a large dataset of urban form variables is used to study that relationship, as urban form can also reveal challenges and problems of urban development.

Understanding urban form can be achieved by classifying land use patterns (Chen 2014, Tsompanoglou & Photis 2013, Zhou et al. 2014). The study of land use change helps to evaluate urban growth and the urbanisation process, as well as to identify the boundaries of urban areas. These boundaries are essential for planning and policymaking since they make it easier to implement more focused and likely successful strategies. Urban morphology, but mainly the contrast between urban and rural land use typologies are also significant variables that influence human activities and, thus, energy use (Steinberger & Weisz 2013). Better planning can be obtained if the energy consumption dynamics and impacts within the urban areas, but also within each different land use typology, are more effectively understood.

In this research, urban form variables are collected to identify land use categories. The analysis of these land use categories gives understanding about the spatial distribution of urbanisation, i.e. the dispersal of urban and rural uses. Furthermore, land use patterns provide information about the actual urban boundaries of cities that administrative borders are slow to update (Tayyebi et al. 2011).

The relationship between the energy consumption given by the energy use metric and those land use typologies is quantified using correlation and scaling laws. This brings forth new information on the spatial distribution of consumption by land use to support the design of actions considering the specific needs of each area. Therefore, the use of urban form

variables to determine land use typologies emerges as a valid option taking into account the growing studies on the link between (sustainable) development and urban form (Lowry & Lowry 2014, Mörtberg et al. 2017, Anderson et al. 1996, Permana et al. 2008, Liu, Ma & Chai 2016).

1.2.3 Correlation and scaling laws

The relationship between energy consumption and urban form variables has been corroborated by many studies (Banister et al. 1997, Dieleman et al. 2002, Handy 1996, Liu & Shen 2011, Holden & Norland 2005, Anderson et al. 1996, Buliung & Kanaroglou 2006, Ewing & Rong 2008, Chen et al. 2011, Liu, Ma & Chai 2016). However, this relationship is complex and thus there are no definitive conclusions, making way to the continuous research. This thesis seeks to expand the investigation by using a high resolution scale and a large urban variables dataset. The relationship is studied by uncovering the variation of operational energy consumption regarding urban form metrics by means of correlation and power-law scaling analysis. The results from these analyses bring new insights about the relationship that may be of benefit to policymakers and planners aiming at the reduction of carbon-based energy consumption. Moreover, the study allows the identification of the spatial distribution of consumption and urban development, helped by the large geographical scale which enables a more focused research.

Correlations are standard and simple analyses that provide valuable information about the relationship between two sets of values. In this work, Pearson product-moment correlation is used due to its consistency and common practice. The application of correlation procedures to describe the relationship between energy and urban form is also found in the literature (Newman & Kenworthy 1989, Mindali et al. 2004), although at different scales and using a smaller number of urban variables. For example, Newman and Kenworthy (Newman & Kenworthy 1989) established a correlation between transport fuel consumption and population density. Other studies also support this development principle, a fundamental concept of the *compact city* (Clifton et al. 2008, Masson et al. 2014, Kellett 2015), but environmental problems and long-term sustainability of urban areas gave rise to counter-research (Mindali et al. 2004, Handy et al. 2005) opposing to that option. The correlations established in this thesis seek to understand the relation between energy and urban metrics without supporting one final solution. For that reason, a large dataset is used to better quantify the influence of one on the other.

The analysis of scaling changes has been used to understand the complexity of urban areas, their internal configuration and the interrelation at different geographic scales (Bettencourt

2013, Cottineau et al. 2016). These changes demonstrate the variation of the socio-economic variables in relation to population (Bettencourt 2013, Arcaute et al. 2015). The results from that variation provide important information about the dynamics of cities by quantifying how city size (i.e. population) influences each individual urban variable. This can be used by planners to anticipate impacts of, for example, population growth on the road network, and thus strategies for a better sustainable development.

The mentioned dynamics of cities are commonly based on the scaling exponent values and regimes. Nonetheless, consensus about those scaling attributes have yet to be established (Arcaute et al. 2015, Louf & Barthelemy 2014b, Pumain et al. 2006, Gomez-Lievano et al. 2016). Moreover, much published literature has paid attention to the variance of socio-economic variables only (Bettencourt 2013, Gomez-Lievano et al. 2016), although some research has examined energy consumption (Gonçalves & Domingos 2014, Oliveira et al. 2014). However, those analyses are fundamentally related to city size (i.e. population) confined to administrative boundaries that generally do not include the entire urban spaces. In this research, scaling laws are carried out for LSOA units, avoiding the definition of city boundaries. Additionally, to understand the variation of energy consumption, a large number of urban variables is used. This allows the recognition of the corresponding scaling exponent and to broaden the knowledge about the consumption change within city limits.

Overall, the use of correlation and scaling laws to study energy consumption at LSOA level results in new information about the dynamics of consumption. This is done by identifying and measuring the proportion of influence of each urban form variable on that consumption. Therefore, this new, expanded knowledge about the variation of consumption and which factors have greater influence over it can be used to derive better energy mitigation actions to challenge the negative effects of highly carbon-dependent energy demand.

1.3 Aims and objectives

The main aim of this research is to study the relationship between energy consumption and urban form. This is carried out by using a large geographic scale and a combined energy use metric of the biggest energy demanding vectors, employing a broad definition of urban form, and the application of simple and replicable approaches accessible to local governments and end-users. The results can inform energy-related policy and planning by identifying energy consumption patterns and distinguishing the urban variables that have bigger effect on consumption. The research work supports, therefore, the following aims and objectives.

Aims:

1. understand the relation between energy consumption and urban form variables at different scales, quantifying the influence of the second on the first, i.e. how the change of different urban variables may affect the increase or decrease of consumption;
2. identify energy consumption patterns at LSOA detail level and integrate the energy costs of buildings and commute transport.

Objectives:

1. present the main urban development typologies to recognize the benefits and disadvantages of each for better energy efficiency planning and energy consumption estimation;
2. formulate a methodological framework to expand and achieve a better understanding of the relationship between urban form variables and energy consumption;
3. introduce a new, simple energy use metric combining buildings and transport to determine per capita energy consumption patterns at high resolution;
4. identify land use typologies derived from a set of physical and socio-economic variables defining urban form to describe the land use in England and help to distinguish the boundaries between urban areas and rural spaces;
5. obtain the correlation coefficients and measure the scaling exponents between energy consumption and urban form at different geographic scales to suggest policy planning guidance and identify actions regarding the mitigation of carbon-energy demand.

The workflow of the research (Figure 1-1) is thus conducted to support the aims and objectives. The outcomes are expected to deliver new knowledge about the relation between energy consumption and urban physical and socio-economic characteristics, specifically the consumption dynamics of growth and decrease at large scale given by correlation and scaling exponent values. This can be used to outline better and more detailed planning strategies leading to the improvement of the energy efficiency of cities, i.e. the energy-optimisation of key urban form variables.

1.4 Thesis overview/structure

The thesis is divided in seven chapters which are arranged into: introduction, methods, results and conclusions. Chapter 2 describes the principal characteristics of the main types

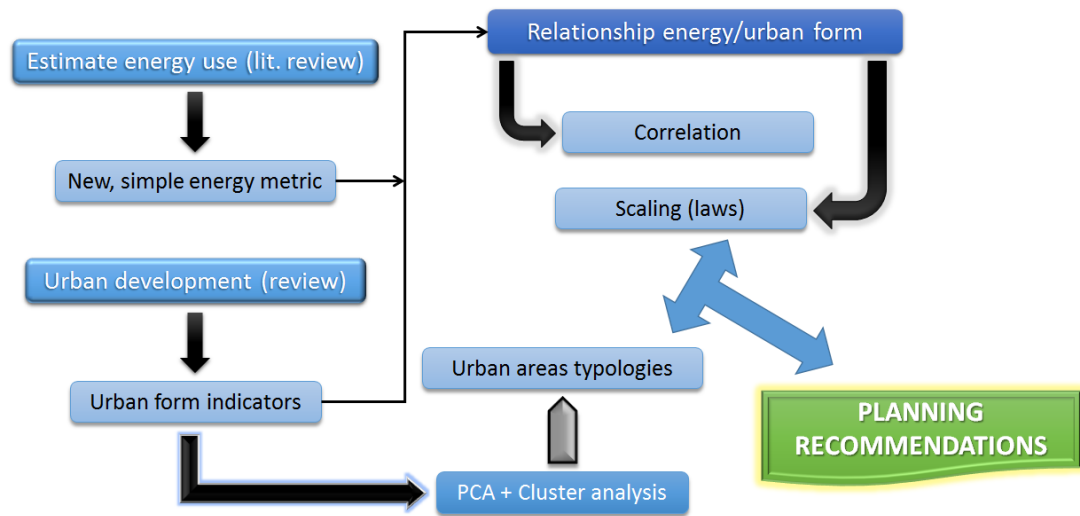


Figure 1-1: Schematic diagram of the thesis.

of urban development, linking them to energy use planning and overall urban planning. Chapter 3 reviews the literature the energy use estimate to tackle questions like: what are the most common methodologies? What are the advantages and the drawbacks of those approaches? Chapter 4 accounts for the framework methodology used to (i) introduce a new, simple energy use metric integrating the consumption of buildings and commute transport (section 4.1), (ii) select an urban form variables dataset (section 4.2) applied to identify land use typologies (section 4.3), and finally (iii) compute the actual relationship between energy consumption and urban form through the use of correlation and scaling analyses (section 4.4). Furthermore, as a methodological chapter, it covers the different procedures to obtain land use classification, as well as providing the framework background of the means used to understand the relationship between energy consumption and urban form. Chapter 5 presents the results of the research. This includes the energy use metric, the land use typologies and the relationship between energy and urban form. The results are described and analysed. Chapter 6 deals with the discussion of the results, investigating the possible planning and policy implications of what is found. Finally, Chapter 7 makes a summary of the results, describing the methodological contribution of the research and application of the outcomes, and sets out future research directions that can be adopted from the findings.

Chapter 2

Urban development and planning

The developing process of human settlements, and mainly the achieved development typologies themselves and the overall urban planning framework, clearly influence the energy use of cities and urban areas (Anderson et al. 1996, Glaeser & Kahn 2010, Wong et al. 2017). That process can be explained by urban form variables (Anderson et al. 1996, Permana et al. 2008, Liu, Ma & Chai 2016). Therefore, understanding the major urban development types and alternatives helps to establish the relationship between urban form variables and energy, i.e. the effects of the first on the latter. This Chapter introduces the main urban development concepts to acknowledge the way the different urban form variables may vary, as well as briefly discusses how the urban planning framework deals with the issue of energy use or demand.

2.1 Energy use and urban planning

Urban population has been increasing mostly since the Industrial Revolution and it is expected that two-thirds of the world's population will be urban by 2050 (UN-DESA 2014, Reinhart & Davila 2016). By concentrating people and many activities, urban areas and cities are also energy-hungry, already representing two-thirds of the world's energy consumption and GHG emissions (IEA 2011, Cajot et al. 2017). Considering the known negative consequences of GHG emissions and carbon-based energy demand such as climate change, the problem has to be faced by governments, decision-makers and planners. Urban planning has a decisive role on the mitigation of those consequences and present strategies and effective actions to tackle the energy problem at different scales. Therefore, urban planning should go beyond traditional city spatial design, but evolve by analysing and taking into

consideration both the quantitative and qualitative aspects of urban form, urban development and quality of life along with concerns about the energy system (Cajot et al. 2017, Hukkalainen et al. 2017). It is important to understand that planning techniques and urban design have to adapt to the always changing urban systems and city evolution process.

Planning for urban areas includes defining land use, urban form layout, building size and type, transportation networks, etc. (Hukkalainen et al. 2017, Yeo et al. 2013). In this process, urban planning decisions can influence the energy systems and energy consumption (Zanon & Verones 2013) at different scales by determining, for example, construction materials and building energy efficiency (Poggi et al. 2017). Consequently, energy demand is affected by urban form, i.e. density, building configuration and morphology, and infrastructure, that result in better energy and resource efficiencies (Ratti et al. 2005, UN-Habitat III 2016, Keirstead & Shah 2011), depending of the implemented actions. This means that appropriate urban form planning and the choice of the overall urban development to follow in a city, region or country exerts a significant effect on a sustainable development outcome. The support for this sustainable development depends, thus, also from the integration of a energy plan in the overall urban planning framework, since energy is one its essential pillars (Prasad et al. 2014, Cajot et al. 2017).

Energy planning is not easy to define, as this can include the three main dimensions of sustainable development – economic, social and environmental (DCLG 2012, Neves & Leal 2010) –, but also technical and even geopolitical aspects (Prasad et al. 2014, Cajot et al. 2017). Nevertheless, a good energy roadmap planning should be based on an effective and spatial balance between energy supply and energy demand. This includes supporting better choices by consumers, ensuring an optimal mix of energy sources to satisfy energy demand, developing appropriate infrastructure, promoting the introduction of new technologies such as renewable energy technologies, and anticipating future changes and economic, social and/or political constraints (Prasad et al. 2014, Cajot et al. 2017). Furthermore, an energy roadmap must be harmonized with the national and supranational goals referring to energy reduction actions and climate change mitigation strategies, making it difficult to design the perfect energy plan. This difficulty comes also from the fact that energy planning is usually dissociated from a single planning authority, but combines many actors, public and private, responsible for buildings, networks and infrastructures design and management. For this reason, general urban planning documents such as the UN's New Urban Agenda and the NPPF mostly draw the attention to the need of better building and transport energy efficiency linked to urban form design and sustainable development (DCLG 2012, UN-Habitat III 2016), since these are aspects over which is expected a more direct influence by governments and planners at different scales: national, regional and local. In this way,

a better understanding of the relationship between urban form and energy consumption, as proposed in this thesis, is assumed as a significant contribution to an overall improvement of an energy planning framework.

The potential improvement of energy efficiency at local scale has been considered an important focus of urban planning in the literature, as local authorities can play a key role in, for example, promoting the use of renewable energy sources and reducing CO₂ emissions through policies (Neves & Leal 2010, Hukkalainen et al. 2017). Though reducing carbon-based energy use goes beyond urban boundaries, local scale actions are essential to enhance energy efficiency, manage resources and achieve sustainable development (Poggi et al. 2017, Hukkalainen et al. 2017, Cajot et al. 2017) in a general urban planning framework. Therefore, local policies such as the location of services, the form of transportation networks and urban form or infrastructure design are good examples of the needed connection between urban planning and energy planning to arrive at energy efficient cities through integrated approaches (Hukkalainen et al. 2017, Amado et al. 2016). Within the energy demand/supply spatial balance planning, the growth of Decentralized Energy Systems (DES), mainly due to the affordability of renewable energy technologies, has been transforming cities and urban areas also into centres of energy production or generation, besides energy consumption (Adil & Ko 2016). In this way, the use of microgrids or smart microgrids, among others, can bring new dynamics to the local energy systems and the overall energy roadmap policy, promoting new forms of reaching sustainable development. However, it is important to understand the social, economic and environmental impacts of DES in long-term urban planning, including the effects on energy infrastructure and urban form resilience and adaptation (Poggi et al. 2017, Adil & Ko 2016).

As mentioned before (section 1.1.3), the definition of urban boundaries have a significant impact on many spatial problems, including urban planning and specifically on energy planning (Calderón et al. 2015). The use of administrative boundaries do not effectively distinguish the split urban/rural use (Masucci et al. 2015, Comin et al. 2016), though in many cases this is still the best approach to spatially estimate energy consumption. Most studies about urban energy planning do not tackle the problem, though recognising the importance of boundaries to arrive at better energy-optimisation and energy efficiency (Comin et al. 2016, Amado et al. 2016). The work in this thesis is developed by using a large scale geographic unit to estimate energy consumption and quantify different urban form variables, covering more than administrative limits, and so preventing defining urban boundaries.

2.2 Sprawl development

Urban sprawl is a complex development typology and thus hard to define, quantify and measure (Frenkel & Ashkenazi 2008, Balta 2016, Johnson 2001). Essentially, it's a form of urbanization with inefficient, low-density and suburban development around the periphery of a metropolitan area or city (Balta 2016, Brody 2013), but other characteristics are associated with it. Starting from the natural growth of population of cities and the unplanned expansion of households at the urban fringe (Ewing 2008), a scattered and discontinuous pattern of development is formed, together with low-density residential areas (Frenkel & Ashkenazi 2008, Yusuf 2014). Sprawl may also result from the re-location of industrial spaces to the hinterland or peri-urban areas due to the need of large site areas, as well as from the increased mobility given by private car ownership (Balta 2016, Brody 2013). At the same time, free-market has also a significant input on sprawl development as a consequence of some landowners withholding land from market in the outskirts (Ewing 2008). Furthermore, subsidizing owner-occupied housing, infrastructure and transportation outside cities also contributes to urban sprawl development (Ewing 2008). Chiefly, two forms of sprawl are identified: (i) suburban sprawl, associated with poverty and slums as working families are driven to establish themselves in the suburbs given the unaffordability of urban centres; (ii) exurban sprawl, when affluent families decide to live on the low-density periphery, given the deterioration of city centres into slums (Yusuf 2014). Accordingly, sprawl is mainly a consequence of population growth, socio-economic factors, political circumstances and physical-geographic characteristics (when topography, water bodies and other impede continuous development) (Ewing 2008, Yusuf 2014, Cox & Utt 2004).

Several patterns of sprawl (Figure 2-1) are mentioned in the literature (Johnson 2001, Ewing 2008) – from leapfrog development to commercial strips –, but here the focus are the characteristics and the impacts of urban sprawl. As mentioned, quantifying or measuring sprawl is not an easy task, but fundamentally can be described as areas of low-density areas, automobile-dependent and with lack of functional open space (Frenkel & Ashkenazi 2008, Ewing 2008, Silva et al. 2007). Independently if the leading pattern is leapfrog development, strip or ribbon development or continuous low-density development, those low-density urban areas favour *McMansion*-type households: large single-family houses with outside, inappropriately mixed features and poor thermal performance and energy efficiency (Mullen 2007, Stead 2008). Additionally, these 'undesirable' land-use areas show automobile dominance and dependency that brings forth several consequences (Balta 2016, Silva et al. 2007). First of all, increases the energy use for transportation, generates more traffic congestion towards urban centres and causes increased air pollution (Johnson 2001,

Silva et al. 2007, Stone 2008). Environmental effects also include the loss of farmland and environmental fragile lands, diminishing of species diversity, increased risk of flooding, environmental deprivation and others (Ewing 2008, Johnson 2001, Mullen 2007). Moreover, the monotonous residential visual environmental of low-density areas decreases aesthetics appeal of landscape and also causes the ecosystem fragmentation (Johnson 2001, Burchell et al. 2000, Ahmadi 2014).

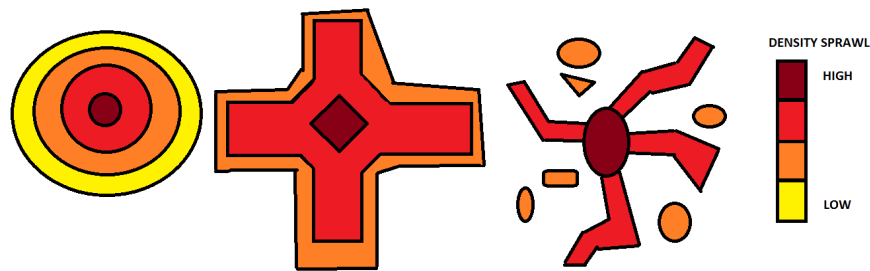


Figure 2-1: Examples of sprawl development patterns. Based on Sudhira *et al.* (Sudhira et al. 2005).

The car-dependency of those low-density areas increases not only transport fuel consumption but also stimulates negative health effects, as obesity and cardiac diseases, because of less physical activity (Eid et al. 2008, Ewing et al. 2006, Leal & Chaix 2011). Positive impacts of sprawl can also be identified, as the stronger citizen participation of smaller government units and lower crime rates, although this generally comes at expenses of racial segregation (single-family housing areas are likely to be more ethnically homogeneous), deprivation of access due to poor accessibility and loss of functional open public spaces (Balta 2016, Ewing 2008, Ahmadi 2014). From a state-governance point of view, sprawl can place other problems: melding neoliberalism with unregulated spaces and cyberlibertarian utopias, the ethnically and/or social homogeneous suburban exclusive communities hold upward mobility and assume the devolution of state responsibility to private sector and parts of civil society (Peck 2011, Ewing et al. 2016, Swyngedouw 2005). This leads to space and local authority government fragmentation where deregulation is pushed forth under the threat of secessionist thinking and a neo-liberal anti-state framework, belonging issues and the chimera of a self-governing city-regions (Peck 2011, Etherington & Jones 2016, Ekers et al. 2012, Neuman 2005). Consequently, private authoritarianism facilitated by capital power from those exclusive low-density communities – in fact sanctioned by the state – may lead to further sprawl.

The growing awareness of the negative consequences from sprawl development and the political and financial associated costs made way to alternative development patterns. The

most common solutions are described next (Sections 2.3 and 2.4), but essentially alternatives seek a transit-friendly, mixed-use design, transit-oriented and high density area development (Johnson 2001, Ewing 2008). It is assumed that higher density areas are more energy efficient than sprawl development and thus are environmentally friendly and sustainable (Silva et al. 2007, Mullen 2007, Williams 1999). Controlling urban sprawl by taxes is also a suggested alternative (Johnson 2001). Nonetheless, some authors consider that the financial costs of sprawl are being overestimated as local government expenditures follow economies of scale (Cox & Utt 2004, Holcombe & Williams 2008, Drew et al. 2012). Although this disregards the environmental effects of sprawl, higher density areas result in shorter trips, and therefore lower fuel consumption. On the other hand, it may also produce higher congestion levels, reversing the decrease of fuel expenditure. *McMansion*-type households are also usually less energy efficient, increasing the energy demand by buildings in that area. Taken as a whole, sprawl development promotes more negative effects than positive and, therefore, actions should be taken to prevent or mitigate it and support more sustainable development, as recognised by the main global and UK national urban planning documents such as the UN's New Urban Agenda and the NPPF (DCLG 2012, UN-Habitat III 2016).

2.3 Compact city

The acknowledgment of the high energy inefficiency and other negative outcomes resulting from the unplanned population growth (Balta 2016, Ewing 2008, Silva et al. 2007) of urban sprawl led researchers and planners to seek alternative development approaches. In late 1980s and early 1990s, some consensus (although academically limited) was achieved suggesting that compact cities were one of the ways to reduce energy consumption and other negative environmental consequences of sprawl development (Breheny 1995, Williams 1999). Characterized by high population density, mixed-use land use and the concentration of businesses and services, compact cities apparently support a more sustainable development and are an advantage to reduce carbon emissions and energy consumption (Breheny 1995, Burton 2000, Neuman 2005). Other benefits include: the protection of the countryside from the pressure of development; the better accessibility to goods and services due to concentration; the encouraging of energy-saving opportunities, as the use of new technologies; the incentive of more sustainable travel modes, as walking, cycling and public transport (Chen et al. 2008, Williams 1999); and other environmental, economic and social advantages. Essentially, making use of economies of scale, compact cities promote travel modal shift, decrease travel by car thus reducing fuel consumption, diminish travel

distances (Poumanyong & Kaneko 2010, Burton 2000, Neuman 2005, Melia et al. 2011) and, mainly, stimulate urban and global quality environments.

Although consensus was only limited, a vast amount of research (Breheny 1995, Williams 1999, Melia et al. 2011, Burton 2000, Neuman 2005, Holden & Norland 2005, Dieleman & Wegener 2004, Kasanko et al. 2006, Tsai 2005) has been published since then discussing and disputing the benefits and applicability of the compact city hypothesis to succeed or to mitigate the negative effects of sprawl development. First, because the positive results from compact development, as the decrease of car travel dependency and the concentration of people, businesses and services, are not always identified (Williams 1999, Melia et al. 2011) in the real world. Additionally, overcrowding, noise and air pollution, increase of traffic congestion are some of the problems resulting from urban compactness (Steemers 2003, Burton 2000, Chen et al. 2008, Melia et al. 2011). In fact, urban intensification contributes to climate change and depletion of resources, and causes increases in transport volumes and traffic concentration that lead to the growth of fuel emissions (Zhang & Lin 2012, Melia et al. 2011). The expected effects on travel are not always achieved since not only population density influences car travel behaviour (and energy consumption overall), but also other variables, as connectivity, accessibility, public transport, parking constraints, land use, jobs/housing balance, settlement size, travel distance, personal choices, environmental beliefs or value system, standard of living and other social, cultural and economic situations (Næss 2012, Larivière & Lafrance 1999, Melia et al. 2011, Collins & Chambers 2005).

Further problems and consequences result from compact development. From a policymaking perspective, the arrangement of the urban form to accommodate urban compactness either increases the density of people or dwellings. The selected course of action will produce different outcomes: the rise of the number of dwellings (and thus households) will certainly expand the already high building energy demand, both embodied and operational energy, and related carbon emissions (IEA 2011, BPIE 2011, US-DE 2008). In England, for example, higher densities do not always correspond to lower energy consumption (Figure 2-2). Although the selected observations in the Figure cover the whole administrative boundaries of each Local Authority (LA), which can lead to overbounding (or even underbounding) of the actual limits of the cities, the expected lower consumption by higher densities is not entirely recognised. In Figure 2-2 this is visible, for example, for Manchester and Leeds, presenting a contrasting energy consumption since Leeds LA includes the surrounding hinterland.

The application of compact city may also result in the increase of population, which will increment the 'town cramming' feeling, deplete resources and decrease environmental quality (Chen et al. 2008, Williams 1999, Melia et al. 2011), among other consequences.

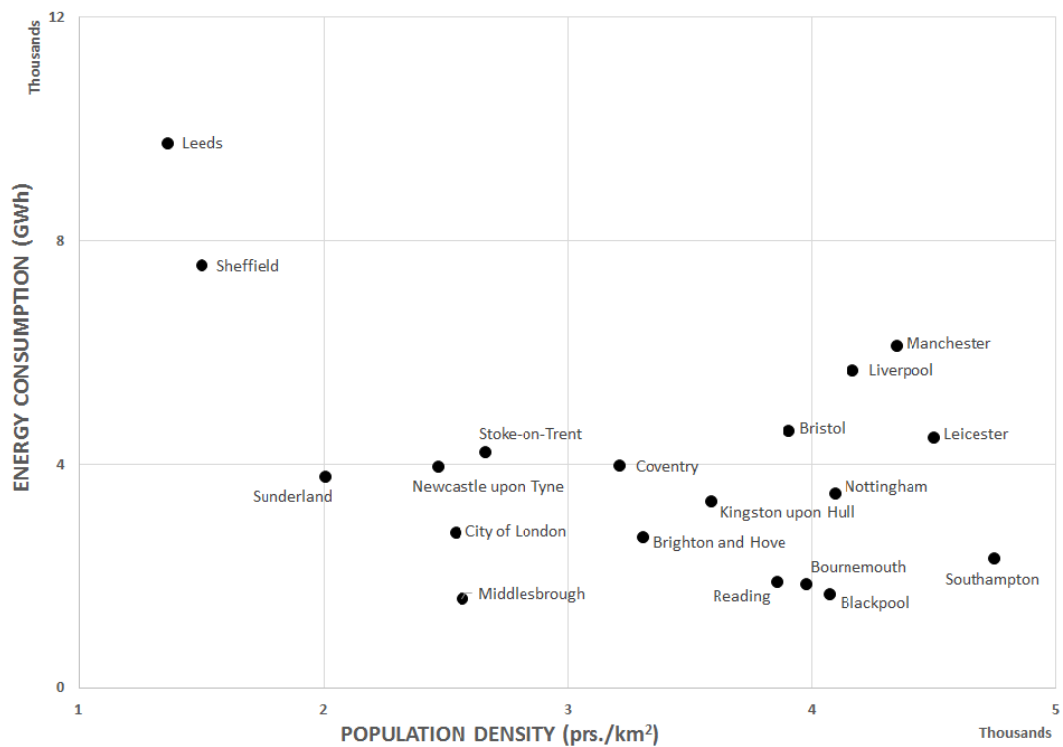


Figure 2-2: Relationship between the consumption of electricity and gas of buildings and population density in selected Local Authorities of England. Based on data published by DECC (DBEIS 2017b) and ONS (ONS 2017).

Moreover, intensification has proved to have negative impacts on social equity and mental health: the boosting of flat-type dwellings in cities generally results in less domestic living space; the risk of developing psychosis, depression and anxiety is higher in denser areas; the decrease of green space environment also highlights social stress; the concentration of people heightens the probability of epidemiological diseases (Burton 2000, Sundquist et al. 2004, Lederbogen et al. 2011, Recsei 2013), and other effects. The developing of new dwellings due to urban intensification also brings pressure to the housing prices (usually increasing) in the neighbouring area contributing to the shortage of affordable family homes (Burton 2000, Whitehead et al. 2015).

The proliferation of non-residential buildings increases energy consumption due to the use of air conditioning and other thermal comfort and indoor air quality systems, as well as the unpredictable occupant behaviour towards those systems (Steemers 2003, Karjalainen 2016). The use of air conditioning and other building mechanical systems are also associated with human health hazards considering that they promote the growth and spread of microorganisms responsible for infections, such as the *Legionella pneumophila* (Gundermann 1980,

Dondero Jr. et al. 1980, Yu et al. 2009). Urban compactness brings further social problems: high-rise buildings blocks are unfavourable to community life and neighbouring communication; overcrowding maximizes noise, poverty and crime levels; concentration emphasizes city dirtiness and congestion (Burton 2000, Chen et al. 2008); and many others.

The urban form and social structure of compact cities are modelled and inspired from the old medieval European cities where people and activities concentrated and converged into a single central area (Neuman 2005, Breheny 1995, 1992). Compact development is advertised as a sustainable alternative to sprawl, even now in such urban planning documents as the UN's New Urban Agenda and the NPPF (DCLG 2012, UN-Habitat III 2016), although various contradictions of its potential benefits, as well as its feasibility and effective applicability, have been raised (Neuman 2005, Williams 1999). At first because urban sustainability definitions vary in literature. The environmental, economic, social and governance dimensions of every community are likely to differ, slightly or significantly, from each other, making it difficult to outline a single best definition of sustainable development (Shen et al. 2011, Maclaren 1996). Thus, many variables can be used to define sustainability. Furthermore, intensifying the urban living experience through high densities and compactness won't bring health and well-being benefits. Actually, the expected *Stadtluft macht frei*¹ ('urban air makes you free') clashes with the city polluted air from transport carbon emissions and other sources that will surely be aggravated by urban intensification (Beck 2014, Harvey 2003).

Even if the core premise of compact city proponents is that it opposes urban sprawl, the expected problems from compactness should be enough to disregard it as an antidote of the latter. Urban form is multifaceted and achieving a sustainable development can't be considered only by development options such as sprawl or compactness. Sustainability, especially in cities, includes different dimensions, from physical characteristics to the quality of life (Neuman 2005, Shen et al. 2011). Responding to the fallacy and paradox of fiercely regulated compact cities, but also to the fragmented land use of sprawl development is a complex process, and present research hasn't found a means of solving it.

2.4 Smart growth

The search for urban sustainability resulted in different alternative options to sprawl development. Smart growth is a complement to compact development, although some early

¹Or *Stadtluft macht frei nach Jahr und Tag* ('city air makes you free after a year and a day'). Although this German principle of law was applied to the liberty of serfs and not the air quality in cities.

literature consider them the same. Similarly, some authors use smart growth and *New Urbanism* interchangeably, but each concept has different origins: the first was introduced by environmentalists, policymakers, citizen groups and transportation planners (Knaap & Talen 2005, Wey 2015); the second was proposed by architects and physical planners to reflect pedestrian-oriented urban life and create healthy and diverse communities (Knaap & Talen 2005, Cabrera & Najarian 2013). Nevertheless, most of the principles of smart growth and *New Urbanism* are the same, though the latter mostly focus on the physical urban form of cities and the potential of market forces to achieve the best development (Knaap & Talen 2005, Cabrera & Najarian 2013).

Smart growth has no detailed, clear-cut definition (Wey 2015, Handy 2005, Schneider et al. 2013), as different organizations, agencies and groups define it in a way to accommodate their own goals and agendas (Ye et al. 2005, Downs 2005). However, six main components or principles of smart growth are commonly accepted:

1. planning, to support and integrate mixed land uses;
2. transportation choice variety, tackling (private) car dependency and encouraging walkable and bicycle-friendly neighbourhoods;
3. economic development, by promoting infill development of existing communities, revitalizing city centres and supporting activity in depressed neighbourhoods already served by infrastructure;
4. housing policies and opportunities, essentially by encouraging compact building and a variety of housing types, sizes and prices that will promote alternatives to single-family houses and increase density;
5. community development, protecting the specific sociocultural values of each community and supporting consensual-made development decisions;
6. natural resource preservation, that includes the safeguarding of open space, farmland and other critical environmental areas by regulatory laws and strict land use (Knaap & Talen 2005, Wey 2015, Ye et al. 2005, Downs 2005).

The majority of the smart growth aspects is urban focused, as given by the integration of land use and transportation (Knaap & Talen 2005, Wey 2015). This integration seeks to obtain shorter street lengths, better accessibility, frequent and reliable public transport, mixture of land uses and higher densities (Wey 2015, Schneider et al. 2013). Shorter street lengths favour bicycle usage and walking (Wey 2015, Schneider et al. 2013). At the same time, investing in light rail transit (LRT) systems enhances the use of public transportation

by the population, although depending on the existing conditions (Handy 2005). In essence, smart growth arises from an environmental perspective (given its origin to oppose urban sprawl) through law regulations, but channels development to support economy, community and (evidently) environment (Knaap & Talen 2005).

The sustainability-focused development of smart growth principles imposes difficulties in its implementation. For example, by imposing limits to the extension of urban sprawl, putting red tape into new developments, and raising population densities, will trigger the opposition of land owners of outlying areas, real estate developers and homeowners of existing and new neighbourhoods (Downs 2005). Furthermore, smart growth policies are frequently associated with the agendas of specific groups (headed by the environmentalists), often with no (or little) support of the citizens/residents (Ye et al. 2005, Downs 2005). As with compact development, with which smart growth shares many characteristics, applying the smart growth principles is full of obstacles that are not always easy to surpass. Challenges to urban sustainability are still yet to be resolved.

From an energy point of view, smart growth is apparently better than urban sprawl or compact city developments, as aims for sustainability and thus lower energy consumption and better energy efficiency. This is visible by the promotion of environment-friendly modes of travel acting as alternatives to private car use. Additionally, encouraging infill development and compact building results in the increase of urban densities, generating better energy use efficiency, which contrasts with the high consuming single-family households produced by sprawl development. Yet, implementing smart growth principles is a complex process because of the outside pressure, the difficult of the actual implementation and the need to demonstrate the positive results from this type of development.

2.5 Summary

Urbanisation is one of the major factors to influence energy consumption and related CO₂ emissions (Al-mulali et al. 2013, Wang, Wu, Zeng & Wu 2016), therefore it is important to understand the different typologies of urban development and their relationship with energy and carbon emissions. Sprawl results from natural urban growth and the urbanization phenomenon by promoting low-density and suburban development around the outer limits of a metropolitan city (Balta 2016, Brody 2013). In addition to the environmental, economic and political consequences of that discontinuous and unplanned expansion of the population, urban sprawl is highly energy-inefficient (Silva et al. 2007, Mullen 2007, Williams 1999), generating increases of energy consumption and CO₂ emissions, especially

regarding transportation. The need for actions to mitigate or reduce those negative outcomes within a sustainable development outlook brought to light alternative options to urban development, as compact city and smart growth.

Both compact development and smart growth originate from the equilibrium theory endorsed by sustainability. However, definitions vary in literature (in fact some authors consider smart growth the same as *New Urbanism*) which lays down obstacles to implement and justify the application of those alternatives. Compact city is inspired from the old centralized European cities and encourages high population densities, mixed land uses and the concentration of activities (Breheny 1995, Burton 2000, Neuman 2005). Fundamentally, compact city development makes use of the economies of scale to promote the decrease of travel by car (to reduce fuel consumption) and to allow sharing of structures by the population (for example transport and water supply networks). Nonetheless, compactness boosts urban intensification – to achieve high densities – that increases noise, air pollution and traffic congestion, among other negative consequences (Burton 2000, Chen et al. 2008, Melia et al. 2011). This paradox effect of compact development challenges the claimed benefits of its application (Melia et al. 2011, Gray et al. 2010). Proposing compact city as the definitive solution to sprawl is disputed due to the multifaceted urban space characteristics. Yet, the negative effects of urban sprawl may be restrained by some of the compact city attributes.

Another suggested alternative to mitigate or limit sprawl development is smart growth. Some of its principles are shared with compact city theory: high densities, mixed land uses, decreased car dependency, and others. Nevertheless, smart growth focuses on the environmental aspect of urban areas or cities, housing policies, communities development and transport diversification (mainly to promote eco-friendly modes of travel) (Knaap & Talen 2005, Wey 2015, Ye et al. 2005). The ambitious objectives of smart growth puts it in the opposing centre of many interests and agendas of numerous groups, raising obstacles to its implementation. At the same time, to achieve the proposed goals, smart growth policies require strong regulatory laws that local governments are not always ready to accept because: (i) authorities seldom challenge established lobbies and interests; (ii) the movement is mostly composed of researchers, transport planners, etc., and there is little support of the citizenry; (iii) the benefits suggested by environmentalists are not yet absolutely proven (Handy 2005, Ye et al. 2005, Downs 2005). Though recognizing the adverse outcomes of sprawl development, the lack of reliable results from smart growth (but also compact cities) gives rise to difficulties to actual change.

Compact city and smart growth are still the best sustainable alternatives to counter sprawl development, despite the difficulties of their application and evaluation, as well as their

individual negative effects. However, since the latter 20th century, an alternative view to the equilibrium perspective of sustainability came to light. This new non-equilibrium theory declares that urban systems are inherently complex, multi-dimensional, variable and likely to change (Hillier & Vaughan 2007, Batty 2005, Ahern 2011). Thus, the sustainability's deterministic *fail-safe* mentality seeking an inflexible design and plan of cities is counterproductive. An integrated systems approach in urban planning practice can be more successful in mitigating the undesirable effects of sprawl development (Bai et al. 2017), specially if an energy roadmap policy to improve energy efficiency of important vectors such as buildings and transportation is put into action.

The non-equilibrium, non-invasive view proposes to build an urban resilience capacity that allows an adaptive behaviour and indeterminate planning of cities to respond to change or disturbance (Ahern 2011, Durack 2001). The city resilience capacity operates not only at an urban form physical level, but also at social, environmental, economic and other urban aspects, and performs at two different scales: within the internal dynamics of cities and encompassing the local-to-regional system of cities tied by a multitude of relations (Ahern 2011, Ernstson et al. 2010). The urbanisation process can shift from a problem to an opportunity by applying different available concepts or practices such as smart, eco-, resilient, information or low-carbon cities (Bai et al. 2017), which will have an impact on urban form, land use and energy consumption.

Sprawl is unavoidable due to urban growth, but its current magnitude presents a problem because of the resulting negative consequences. Nevertheless, at the same time, none of the alternatives seems to completely solve sprawl's effects, and additionally may also bring negative outcomes on their own. A different alternative is fixing sprawl development (Dunham-Jones & Williamson 2008, Tachieva 2010, Talen 2015), a theory that acknowledges the volatility of cities and their probability to constant change. This sprawl *retrofitting* shifts the focus from restriction to repair or rectification of the effects resulted from fragmented development (Tachieva 2010, Talen 2015). Repair strategies include infill development, re-converting failed business ventures, transform brownfield areas and reorganize or reconnect communities (Tachieva 2010, Talen 2015), among others, also mentioned in the UN's New Urban Agenda and the NPPF (DCLG 2012, UN-Habitat III 2016). However, this alternative experiences some of the same problems of the other solutions: practical results are still different from the expected theory.

In general, there is no definitive solution to sprawl development – no alternative is flawless. Yet, it is still important to deal with its negative effects to protect communities and ensure their sustainability. The focus of this research is to understand the impacts of different urban form variables on energy consumption, assuming that urban form can characterize

the distinct development types. Development stages and typologies influence energy consumption: sprawl development is associated with energy inefficiency, contrasting with the conventional better energy efficiency of compact cities and smart growth. The use of urban form variables assists planners and policymakers to understand those development stages that then can be related with energy.

2.6 Contributions to the research

In this chapter, an overview of urban planning, energy planning and urban development types is presented. It is shown that an energy planning is not always considered or specified in the overall urban planning framework strategies, though a close association between them is recognised. However, urban planning documents such as the New Urban Agenda and the NPPF (DCLG 2012, UN-Habitat III 2016), as well as the the majority of the current research (Calderón et al. 2015, Amado et al. 2016, Hukkalainen et al. 2017, Masucci et al. 2015), places urban form design and its relation with energy in the spotlight of energy planning to achieve energy efficiency and sustainability in urban areas. A better understanding of that relationship is expected to provide new knowledge to arrive at a reduction of carbon-based energy consumption and overall sustainable development.

In this work, the relationship between the urban physical and socio-demographic variables (i.e. urban form) and energy consumption is statistically computed. Land use typologies are also identified using those urban variables, followed by the correlation and scaling relationship assessment between energy and urban form by land use type (and for the total LSOAs). The correlation and scaling exponent values will give information about the energy efficiency of each land use category. By associating land use with development type and stage, the results of this thesis will provide new knowledge about which (if any) should be preferred to obtain better energy efficiency in the urban areas of the case study.

The results of this thesis deliver information about the link between the variation of energy consumption and development types via urban form variables, which later can be used to outline more detailed and focused strategies to reduce consumption through a better understanding of the influence of the urban variables. Although this thesis main goal is not to suggest alternative development typologies, nor to identify the present development types in England (by LA or LSOA units), the new information will indicate the location of less efficient areas. This identification provides new knowledge about the real consequences of the distinct types of development on energy consumption, contributing to the vast literature on urban development and advancing the knowledge on sustainable development.

Chapter 3

Estimating energy use

Urban energy demand is mainly attributable to buildings and transport (Banister et al. 1997, Hickman & Banister 2014). The energy consumption of both is highly interdependent because of the influence of the urban spatial layout on the mobility of the building users' and their respective travel distances that have an effect on, for example, the carbon footprint of transport (Stephan et al. 2012). Transport networks, specifically, affect the operational energy consumption of both buildings and transport (Hillier & Vaughan 2007) since it is the means of carrying individuals and goods between locations (Barthelemy et al. 2013). Therefore, it is of vital importance to measure their energy consumption to be able to outline and implement mitigation strategies that reduce, mostly, the carbon-related energy consumption.

Estimating the energy consumption of buildings and transport is a complex process since it is unfeasible to quantify the consumption of every building or vehicle, particularly in large areas such as cities. This is especially compounded when looking at a neighbourhood geographic scale and related to a network of buildings. Various approaches have been used to estimate energy consumption (Howard et al. 2012, Fumo 2014, Heiple & Sailor 2008, Wang 2008) but there is no definitive solution yet. However, the Brundtland Report (Brundtland et al. 1987), the Rio Conference (Panjabi 1997), the Kyoto Protocol (Grubb et al. 1999) and, more recently, the Paris Conference on Climate Change (Dimitrov 2016) have put the reduction of carbon emissions and energy consumption based on fossil fuels into the forefront of energy-related research. This has resulted in a large number of academic papers (and other documents) about energy consumption being published over the last few years.

The review that follows presents an overview of the common approaches and methodologies

to estimate energy consumption, analysing key publications, identifying particular strengths and weaknesses and even gaps in the current literature. Nonetheless, this literature review does not claim to be systematic, thorough or exhaustive, but to introduce the typical and general methods used to measure or estimate energy consumption. By doing this, a comparison with the proposed new, simple energy use metric (see Section 4.1) can be achieved to give grounds for the suggestion of this metric. This energy metric seeks to introduce a novel approach that is more end-user friendly, based on accessible data sources, combines buildings and transport, has the prospect of being replicable and easily carried off by planners and policymakers that search for better strategies and actions to reduce carbon-related energy consumption. The review of methodologies to estimate energy consumption is conducted to buildings and transport alone, as well as combined approaches, i.e. methods that integrate the estimate of consumption of both vectors.

3.1 From buildings

The energy consumption of buildings is mostly related to space cooling and heating, domestic water heating and electricity (Howard et al. 2012). Increasing energy prices and questions about sustainability have made buildings a focus of energy efficiency policies, which can represent between 30% and 40% (sometimes more) of the total energy consumption (Stephan et al. 2012, Eurostat 2015).

The longer life span of buildings compared with other energy consumption factors and the high dependence of populations from these puts buildings in the spotlight of research on energy efficiency. The efficiency improvement of systems, materials and other important components that integrate buildings has been the main concern of research, although not all methods consider the actual estimate of energy consumption of those buildings. Follows a review of common approaches and important articles published in recent years that illustrate the prevalent methodologies used to estimate energy consumption of buildings.

3.1.1 Key methods and publications

A significant number of papers about energy use in buildings have been published over the years. This Section reviews selected articles deemed significant if presenting common approaches and also valuable and/or new approaches to estimate energy consumption. The selection of papers, while somewhat subjective, favours articles that illustrate some of the most cited and relevant examples to estimate and/or model consumption of buildings or its

components. Overall, the review of the following papers identifies the characteristics of the frequent approaches to estimate buildings energy consumption. These approaches contrast with the distinct procedure undertaken in the mentioned energy use metric (Chapter 4.1).

3.1.1.1 Modelling

A common approach to estimate energy consumption is setting up a model representing the real world's complexity to get a better understanding of its dynamics. Models are created to simulate and estimate current and future consumption, mostly through computer simulation. The complexity of models varies but the level of intricacy may result in difficulties to implement and use them in different regions. The following are examples of these type of models found in the literature: (i) estimation of end-use energy of buildings in New York City (Howard et al. 2012); (ii) urban energy consumption and CO₂ emissions in Beijing (Feng et al. 2013); (iii) residential and commercial buildings hourly and seasonal energy consumption estimate (Heiple & Sailor 2008); (iv) EnergyPlus (Crawley et al. 2000, Gerber 2014). The latter is a building performance simulation software (Crawley et al. 2000) that has been used by different authors to estimate the total energy consumption of residential and non-residential buildings, or some of the various user-configurable buildings subsystems (Fumo et al. 2010, Henninger et al. 2004, Jakubiec & Reinhart 2011). Whilst enabling very detailed estimates of energy consumption, the model's complex procedure limits its large-scale application to vast geographic areas. Additionally, the model demands a lot of input data that is not generally available for all cities or urban areas.

The remaining models seek to identify energy consumption patterns or profiles (Howard et al. 2012, Heiple & Sailor 2008) and related CO₂ emissions, as well as simulating their future values (Feng et al. 2013). As essentially bottom-up approaches derive from statistical data, these models are limited by the scope and accuracy of this data; e.g. specified statistics focus on a city or region. On the other hand, the use of computer simulations typically present two important limitations: (i) frequently, the lack of suitable, accurate and reliable data (Yang et al. 2014); (ii) compulsory coding of variables that cannot always be estimated (Cioffi-Revilla 2014, Sacks et al. 1989), such as human behaviour. For example, the energy estimates of the first model (Howard et al. 2012) rely mainly on annual energy consumption values, but do not include actual occupancy patterns (Swan & Ugursal 2009) or buildings configurations, restricting its use for long-term planning strategies. The importance of socio-economic factors on energy demand is recognised by their inclusion in the second model (Feng et al. 2013), while also acknowledging the need to refine the model framework to describe internal dynamics.

3.1.1.2 Household behaviour

The significance of socio-economic factors to model energy use is demonstrated in a study discussing the correlation between demographic and economic household characteristics and their energy consumption (Longhi 2015). The analysis shows that household size has higher impact on energy expenditure than other characteristics such as income, presence of people of pensionable age and those who are jobless. This finding contrasts with another study (Kaza 2010) where housing type was deemed as having a higher impact on residential energy consumption. Many other papers (Wilson & Dowlatabadi 2007, Brounen et al. 2012, Brandon & Lewis 1999, Mansouri et al. 1996) have also been published about the subject. While these acknowledge the effect that the individuals' decisions have energy consumption, the lack of data and the complexity of quantifying human behaviour is identified as a hindrance to better studies.

Most often, estimates of the energy demand of residential buildings only consider operational energy (Sartori & Hestnes 2007, Gustavsson & Joelsson 2010). However, embodied energy can (in some cases) make up about 45% of the total budget of a residential building over a 50 year period (Crawford 2011). A large number of papers have been published concerning this matter (Stephan et al. 2012, Shao et al. 2014, Zhang et al. 2015, Thormark 2002, Dixit et al. 2010). Although not all of these studies include a life-cycle analysis of the case study buildings, the results generally show that a holistic perspective of energy consumption should be embraced (Casals 2006, Szalay 2007), as it potentiates a better design of policies to reduce consumption. A prevailing limitation of these studies is the use of predetermined building typologies, which restricts the implementation of those models and the research findings.

3.1.1.3 The boundaries issue

Another major barrier to estimate energy consumption is defining the boundary of urban areas. Different urban/rural classification systems reveal different figures for energy consumption. Parshall et al. (Parshall et al. 2010) present a methodology to calculate energy consumption and CO₂ emissions based on an US national inventory data called Vulcan (Gurney et al. 2009), which distinguishes between urban and rural areas. The Vulcan inventory is overlaid with various classification systems for urban spaces to obtain fuel consumption estimates of buildings and transport. Larger differences in consumption estimates are found for urban areas, emphasizing: (i) the need to create a standardized definition of those areas (Satterthwaite 2008); (ii) the requirement to produce a data inventory at local scale (Brown

et al. 2008). Therefore, properly identifying urban areas is a crucial step to support efforts to reduce energy demand and implement low-energy and low-carbon strategies, as shown by (Inouye et al. 2015, Barredo et al. 2003) and others.

3.1.2 Summary

Estimating a building's energy consumption is a complex process, and estimating that of a neighbourhood or network of buildings more so. At present there is no unique, best, approach to the problem. The methodologies found in the literature consider different approaches, but most are physically-based models. The reliability of these models and the results obtained can be questioned (Seibert 1999), although some type of modelling is always required when evaluating reality (Snowling & Kramer 2001), particularly for such complex systems. A possible way to assess and improve the reliability of any model is validating the model's predictions against independent data (Gardner & Urban 2003).

Another limitation of using models is their reliance on different data sources with distinct quality criteria and scales. Better standardized data at large scale (Brown et al. 2008, Calderón et al. 2015) is therefore needed. Moreover, the majority of the approaches are applied to specific cities (or set of cities) and/or typologies of buildings, that generally cannot be used in different scenarios (regions) and larger scales. The highly complex processes that some approaches follow may also be an obstacle to the replicability of those methods to other regions.

Furthermore, some research deals mostly with the efficiency performance of buildings and their systems (Ratti et al. 2005, Costa et al. 2013, Krarti 2016, Nguyen & Aiello 2013, Shaikh et al. 2014) but not their actual energy consumption. Even though more efficient buildings can potentially help to reduce energy consumption, from an urban planning perspective, consumption estimates should also be considered. Additionally, including the human behaviour framework into energy demand estimate (Keyvanfar et al. 2014, Pisello & Asdrubali 2014) should allow the designing of better consumption reduction strategies.

Another major hindrance in estimating urban energy consumption is the definition of the urban boundaries. Different urban/rural classification systems exist and produce different figures for energy consumption. Urban boundaries change over time, but administrative definitions can be slow to follow (Tayyebi et al. 2011, Steinberger & Weisz 2013, Marcotullio et al. 2014). These administrative boundaries of cities, in particular large cities, usually do not cover the whole urbanised area relating to a city. This also raises obstacles for planners and policymakers who may have to use unreliable energy estimates to design actions to

reduce/mitigate consumption (Steinberger & Weisz 2013).

The research in this thesis proposes an alternative approach to estimate the energy consumption of buildings. The methodology includes the use of readily available data sources, the combination of the consumption of buildings with the one from commute transport and the use of LSOA units as a proxy of a large geographical scale (see Chapter 4.1). Furthermore, the whole process is imagined to provide simple and replicable procedures that may be used by local governments, differing from the complex approaches aforementioned.

3.2 From transport

Urban transport energy consumption results mostly from road transport and railways (Johansson et al. 2014, Pandey & Venkataraman 2014). Although the transportation of goods to urban areas using maritime and aviation transport generate energy-related carbon emissions, this is concentrated in a highly connected network of cities with large seaports (Jacobs et al. 2011). As the current review is focused on general urban areas, only road and rail transport are included in the analysis of transport energy consumption.

3.2.1 Key methods and publications

Calculating transport's energy consumption is also not an easy task due to the sector's heterogeneity and the combination of diverse travel modes. The most common approaches are based on models, simulation models and time-series analysis. Simulation models are usually supported by time-series data and produce valuable forecast of transport's future energy needs. By estimating scenarios, actions to reduce GHG emissions by transport may be designed; for example, introducing more efficient fuels or vehicles (Gilbert & Perl 2013) or other technological solutions (Chapman 2007, Greening et al. 2000, Wang et al. 2014, Sperling & Lutsey 2014). Optimization and efficiency are key words used in the discussion of reducing the carbon output of transport, mostly the passenger sub-sector, as it is assumed that increased fuel efficiency reduces the petroleum dependency of the transport sector (Brand et al. 2013, Qian & Eglese 2016, Ajanovic, Schipper & Haas 2012).

3.2.1.1 Energy efficiency

Two important energy efficient approaches have been put forward in recent years: (i) Intelligent Transportation Systems (ITS), a transportation management tool to enhance safety

and efficiency (Weiland & Purser 2000, Dimitrakopoulos & Demestichas 2010, Beresford & Bacon 2006); (ii) eco-driving, not a technological solution but an individual action behaviour associated directly with climate change mitigation (Barth & Boriboonsomsin 2009, Alam & McNabola 2014, Staubach et al. 2014). However, as demonstrated by some authors (Chapman 2007, Greene & Wegener 1997, Anable & Boardman 2005), launching a technological revolution in transport does not resolve the problem. There is the need to change people's behaviour towards travel (Burnett & Hanson 1982, Bamberg et al. 2003, Ahmed & Stopher 2014) and transport dynamics. It was found, for example, that the driving behaviour can influence commuting distance travelled and fuel consumption, and even when interventions are introduced to commute, past behaviour has a significant impact on later travel behaviour and travel mode choice (Chapman 2007, Bamberg et al. 2003, Ahmed & Stopher 2014, Lyons & Chatterjee 2008). Consequently, the reduction of transport's fuel consumption and the improvement of efficiency should also take into consideration (and try to influence) human behaviour.

3.2.1.2 Simulation modelling

The use of models is mainly applied to estimate and forecast future fuel consumption, transportation's CO₂ and other GHG emissions, study travel behaviour and many other transport-related activities. These models vary in their framework, purpose and objectives: some deal with the whole transport sector, others focus on the freight or private car sub-sectors. From the numerous simulation models found in the literature, the following illustrate some common approaches: (i) private car fuel consumption forecast model in Andorra (Travesset-Baro et al. 2016); (ii) bottom-up model predicting freight transport energy consumption and GHG emissions in China (Hao et al. 2015); (iii) a complete transport carbon and energy life-cycle estimation model for the UK that integrates some socio-economic indicators (Brand et al. 2012); (iv) a transport energy consumption and CO₂ emissions model to estimate future trends of the sector in China (Yin et al. 2015). Other authors seek to produce models to assess the total fuel consumption (Wang 2008) and GHG emissions (Cappiello et al. 2002) of a region or country based on car-related data such as engine efficiency, fuel demand, car speed, etc. Predominantly, these models (simulation or otherwise) require a great amount of input data. This restricts their use and implementation, as such a large amount of detailed and disaggregated information is not always available or accurate (Kleijen 1999, Buchholz & Kriege 2014). The lack of data also prevents proper comparisons (Refsgaard et al. 2014, Bańbura & Modugno 2014) between different interconnected cities/urban areas or regions and countries.

3.2.1.3 Time-series

Comparisons between transport energy consumption of different regions or countries is usually carried out via time-series (TS) analysis. Time-series analyses are important approaches to understand transport energy consumption and CO₂ emissions patterns (Ong et al. 2012, Schipper et al. 1992, Lynn et al. 1996). Depending on the data, these approaches enable the disaggregation of consumption by sub-sector, travel mode and fuel type, which may be helpful to planners designing mitigation measures. Nevertheless, this disaggregation is always dependent on data availability, which may be a major obstacle to develop better research. For example, data related to transport energy use in the UK is collected and published by several organizations (DBEIS 2017a, DfT 2017, ONS 2017). The use of different data sources may result in mismatched energy consumption estimates when comparing distinct cities or urban areas.

A great deal of the TS research (Kwon 2005, Papagiannaki & Diakoulaki 2009, Timilsina & Shrestha 2009) also decomposes and identifies the factors that most contribute to the increases of carbon emissions. Moreover, these studies decoupling transport carbon output by sub-sector, fuel type, travel mode and so on provide important tools for planners to address the energy efficiency of transport. Time-series research is valuable but usually cover the whole transport sector (or sub-sectors) of a given region (Zhao et al. 2016), country (Kwon 2005, Danielis 1995) or set of countries (Schipper et al. 1992, Lynn et al. 1996, Timilsina & Shrestha 2009). A comparison between different cities or between urban and rural areas is often too difficult or complex to perform for such large datasets as from a whole country. Consequently, the design of mitigation strategies is limited to small cartographic scales and applied on a general scope. In this thesis, only large scale information on commute transport to work is used to avoid the issue of using different data sources with distinct quality collection methods.

3.2.2 Summary

The transport sector is often considered a driving force of economic growth (Franc & Sutto 2014, Tian et al. 2014), but it is responsible for numerous problems such as congestion, pollution, stress and other negative impacts. Many studies have been focused on reducing those impacts and aims to design strategies to mitigate them. An appropriate estimation of the sector's energy consumption will benefit the outline of these strategies (Franc & Sutto 2014, McKinnon 2007, He et al. 2005).

As with buildings, there is no unique or best way to estimate the energy consumption of

the transport sector. Much of the current research is focused on obtaining better fuel or vehicle energy efficiency, but also on prediction of fuel consumption. The total energy consumption and/or carbon emissions from transportation is also found in the literature, although the heterogeneity of the sector leaves way to further improvement and research. Though many government agencies produce and publish data on transport's energy use and fuel consumption, the estimates are usually incomplete and for small geographic scales. Better policy is always achieved with better information (Ajanovic, Dahl & Schipper 2012) and in the case of the transport sector this is essential due to its reliance on fossil fuels that generate carbon and other GHG emissions.

The work in this thesis introduces a new energy use metric that integrates the energy consumption of buildings and commute transport (see Chapter 4.1). The approach aims at local authorities and general end-users by using a simple and replicable methodology based on statistics published by official sources, and considering large detail scale. This diverges from the complex methods aforementioned, generally of complex nature, which do not favour replication.

3.3 From combined approaches

Urban spaces are complex systems composed of (i) buildings linked by space and (ii) human activity interactions where both buildings and transport interact in a complex dynamics (Hillier & Vaughan 2007, Barthelmy et al. 2013, Batty 2005, Bettencourt et al. 2007, Marshall 2009). A combined approach to study energy consumption in cities or urban areas is often considered more advantageous to ensure a more sustainable planning and energy use optimization (Moghaddam et al. 2014, Østergaard & Sperling 2014, Pasimeni et al. 2014).

3.3.1 Land use and transport

Research exclusively tackling integrated approaches that combine energy consumption of buildings and transport is not yet very common. Most studies address consumption and GHG emissions of transport alone (Traveset-Baro et al. 2016, Hao et al. 2015) or alternatively disaggregate the energy use of buildings by sector, sub-sector, type of fuel (Li & Chen 2013, Nejat et al. 2015) or focus on buildings' systems alone. However, two main alternatives have been put in practice: (i) land use and transport studies; (ii) sector energy use research, as mentioned earlier. Though the land use component does not estimate

energy consumption of buildings, the study of the relationship between land use and transport allows a partial understanding of the urban system dynamics and respective effects on energy demand.

Land use and transport are inherently connected (Giuliano 1995, Cervero & Landis 1995, Wegener & Fürst 2004, Li et al. 2014) due to the necessity of transportation promoted by spatial development (Wegener 2004, Lautso et al. 2004, Hesse 2010). Nonetheless, land use is never static, since cities are living entities (Newman & Kenworthy 1996, Hinchliffe & Whatmore 2006). Transport is only one of the elements shaping the mutation of land use (DfT 2014) and vice versa.

The arrival of the automobile provided freedom in space and time (Wegener 1995, Costa 2007) but disrupted the link between land use and transport, since it allowed the arbitrary allocation of land to residential and commercial use (Newman & Kenworthy 1996), reshaping urban development. The dependence on automobiles brought many consequences to cities and urban areas (Kenworthy & Laube 1996), such as changing the dependent correlation between the locations of households and workplaces. The *New Urbanism* movement arrived to reconnect land use and transport by minimizing automobile dependence and reducing its environmental effects (Newman & Kenworthy 1996, Bohl 2000, Ellis 2002). On that account, Land Use and Transportation models arose to outline a novel urban transit-oriented development (Newman & Kenworthy 1996, Talen 2014).

3.3.1.1 LUT models

The main goal of Land Use and Transportation (LUT) or Land Use Transport Interaction (LUTI) models is to describe the purpose of each piece of land and understand the change of land use in a city or urban area (Wegener 2004, Renner et al. 2014). These models estimate travel demand (Sivakumar 2007, Geurs & Van Wee 2004) and evaluate the results of transport, land use and environmental policies on that demand (Wegener 2004, Renner et al. 2014, Webster et al. 1988). From this travel demand estimation, the energy use (or fuel consumption) may be deduced, though this is not the main goal of LUT models. The first generation of LUT models brought (i) simple static models and (ii) incorporated the maximum entropy principle. Static models do not model data before performing simulation, i.e. do not consider the land use dynamics. On the other hand, maximum entropy models assign land use values according to probability distributions: considering the degree of randomness of the system and stated partial prior data, values are allocated by the principle of uncertainty.

Lowry's Model of Metropolis (Lowry 1964) was one of the first LUT models. Essentially, it was a static model driven by gravity concepts to understand the spatial distribution of activities (Sivakumar 2007, Srinivasan 2000). Therefore, following an analogy to Isaac Newton's law of gravity applied to urban areas, the model reveals that larger cities attract more people, goods, activities, etc. than smaller cities, due to better accessibility (Haynes & Fotheringham 1984, Mayo et al. 1988). Distance is, thus, considered the ultimate deterrent to travel (Haynes & Fotheringham 1984, Mayo et al. 1988).

LUT models do not also consider environmental impacts, energy consumption and economic productivity issues, mainly due to the use of the four-step model to represent transport (Sivakumar 2007, Keirstead & Sivakumar 2012). The four-step model is a sequential travel forecasting procedure to determine the equilibrium of flows in transport (McNally 2007, Iacono et al. 2008). The four steps are: (i) trip generation to calculate trip frequency of Origins or Destinations (OD); (ii) trip distribution, determining trip attraction from those ODs; (iii) mode choice to measure trips by transportation mode; (iv) route choice, assigning each OD trip to a route (McNally 2007).

Second and third generations of LUT models introduced further changes to travel demand modelling. At first, the general equilibrium theory was included to assume that an equilibrium exists in terms of transport supply and demand (Li & Gong 2016). However, the behavioural outlook of these models is still not entirely realistic (Keirstead & Sivakumar 2012). The paradigm change of the third generation of LUT models was the introduction of agent-based microsimulation models to travel demand modelling (Wegener 2004, Sivakumar 2007, Axhausen & Gärling 1992). The application of microsimulation methods to focus on individual agents, instead of the aggregate of flows of people, goods and resources, allows a better disaggregated representation of time and space related to travel demand. Nevertheless, the large amount of data and computational effort to operate these models (Keirstead & Sivakumar 2012), as well as the incomplete view of the costs and benefits of the transport system (Lynde & Richmond 1993, Seitz 1995), suggests that further research is needed. The use of GIS may overcome these problems and help to understand the effects of space on travel behaviour (Maat et al. 2005, Fan & Khattak 2008) and quantify fuel consumption. Overall, LUT models are considered complex, alternative methodologies that wouldn't support the aims and objectives of this thesis, mainly because energy consumption is not actually obtained (directly), but also for the long run-time and others.

3.3.1.2 Agent-based models and examples

Since Lowry's model (Lowry 1964), many more models have been developed. Wegener (Wegener 2004) makes a comparative review of twenty contemporary urban LUT models, noticing that their spatial resolution is as yet too coarse to outline policies and effects at neighbourhood scale (Wegener 2004). The application of the microsimulation technique to activity-based modelling may mitigate this difficulty and enable the understanding of the complex spatial behaviour of individuals on a one-to-one basis (Miller 1997, McNally 1996). The microsimulation approach of agent-based models can be used to more readily analyse and represent the evolution of complex systems (Renner et al. 2014) to model, for example, the heterogeneous behaviour and attributes of urban spatial systems (Salvini & Miller 2005).

The following are the most recent developed agent-based models: (i) ILUTE (Integrated Land Use, Transportation and Environment), the most detailed model available; (ii) ILU-MASS (Integrated Land Use Modelling and Transportation System Simulation), that mostly regards the natural environment; (iii) UrbanSim, the more flexible, expandable and appealing to apply in other regions (Renner et al. 2014, Miller & Salvini 2001, Waddell et al. 2005, Strauch et al. 2005, Beckmann et al. 2007, Waddell & Ulfarsson 2004, Borning et al. 2008).

3.3.2 Summary

Combined carbon-related energy consumption estimates are beneficial since most of the urban carbon emissions originate from both transport and buildings. However, combined approaches are not yet fully developed and most studies tackle energy consumption (and related GHG emissions) of transport or buildings alone. Alternative methodologies to these sector focus are still found, as for example LUT models.

LUT models are alternative integrative approaches, combining land use and transport. These models evaluate travel demand and forecast a population's travel needs (Sivakumar 2007, Iacono et al. 2008), but do not actually estimate energy consumption of buildings and transportation. Furthermore, the highly complex structure of these LUT models demands long run-time and a sizable hard disk space to compute the process (Waddell 2012). Their complexity, together with their need of large datasets and some lack of flexibility makes it difficult to replicate LUT models to other regions or areas apart from a few case studies. Therefore, and from a policymaking outlook, better alternatives to LUT models and sector focused approaches are necessary. Future research should combine and measure

the energy consumption of the urban system as a whole. This integration of buildings and transport would be advantageous to outline strategies that reduce and/or mitigate energy use (Østergaard & Sperling 2014, Pasimeni et al. 2014).

3.4 Summary of literature

The estimation of urban energy consumption is a complex process due to the intricate systems and dynamics that compose urban areas (Hillier & Vaughan 2007, Batty 2005, Marshall 2009), and currently there is no unique, best approach. Buildings and transport are the main consumption vectors in urban spaces, but most approaches study the energy consumption of each vector alone and not combined. For buildings, many methods are based on physically-based models. These models are usually highly complex, rely on different and sometimes too detailed data sources with distinct quality and scales, and are hardly replicable beyond some case studies. Furthermore, some research tackles the energy efficiency performance of buildings and their systems, as the improvement of HVAC (Heating, Ventilation, and Air Conditioning) (Leavey et al. 2015) systems and the building design (including retrofit measures) (Clarke 2001, Kibert 2012), and not the actual estimate of energy of buildings. Though better efficient buildings may potentially reduce their energy consumption, planners and policymakers ask for better information of consumption patterns to be used in the design of strategies that reduce carbon-related energy consumption.

The energy consumption of the transport sector is mostly based on fuel consumption. Around the world, many government agencies collect and publish data for that consumption, as well as the related carbon emissions of transportation. However, the sector is heterogeneous and diverse, making it difficult to gather a full datasets which are often incomplete and at small scales. Consequently, the use of models (Travesset-Baro et al. 2016, Yin et al. 2015, Hao et al. 2015) to estimate energy consumption of transport is frequently found in the literature. The usage of models has the same problems as mentioned to buildings: complexity, reliance on different data sources and the difficulty of replicate the methods to different regions. The collection of detailed information is even more difficult to transport due to the heterogeneity of the sector, increasing the issue of the replication of methods to different cities and urban areas. This will raise obstacles to planners and policymakers that will depend on incomplete or small-scale energy estimates of transport's consumption to draw energy mitigation actions. Moreover, much transport energy research discusses the launch of technological solutions to mitigate fuel consumption and reduce the dependence on fossil fuels (Urbanchuk 2009). Better fuel or vehicle energy efficiency may reduce consumption, but many studies recognise that making changes to human be-

haviour towards a more efficient energy use (Froehlich 2009) is essential to reduce energy consumption at long-term. For example, promoting transport modal shift, mainly related to commute travel, would ultimately reduce fuel consumption and the associated GHG emissions of private car usage.

In addition to sector-based estimates, combined approaches integrating the energy consumption of both buildings and transport were looked in the literature. Combined methods are advantageous because consider the main consumption vectors in urban spaces – buildings and transportation –, benefiting strategies aiming at mitigating carbon-related energy consumption and associated GHG emissions. Nevertheless, most research is not focused in combined approaches, though alternatives are found. LUT models (Sivakumar 2007, Iacono et al. 2008) are popular integrated alternatives, combining the interaction of transport demand with land use. However, the energy consumption of buildings is not estimated and transport's expenditure is obtained indirectly. The impact of human behaviour is also under-represented on transport's travel demand. Furthermore, these LUT models are highly complex and demand long run-time and data for better results which, for example, local governments usually cannot get hold of.

Regardless of the used approach or methodology to estimate energy consumption, most present other issues: (i) lack of an urban planning perspective; (ii) use of different definition of urban areas. If the first will influence long-term strategies that seek reducing consumption, the latter has an effect on the accuracy and reliability of the obtained energy consumption estimates handled by planners and policymakers. As a result, designed and delivered actions may be based on biased consumption patterns (Steinberger & Weisz 2013) and pointed at wrong targets. Collecting data for predetermined outer limits can diminish the inaccuracy of energy consumption estimates of a given city or urban area.

In summary, the analysis of the literature on estimating energy consumption shows the following:

1. reliance on physically-based models;
2. use of highly complex models hard to replicate to other regions;
3. usage of small scale analyses and too detailed datasets;
4. much research focused on energy efficiency variables instead of consumption;
5. neglect of the human behaviour impact in energy use;
6. lack of urban planning perspective;

7. use of different urban/rural classification systems that produce varied estimates;
8. neglect of time-series data in analyses;
9. underdevelopment of combined models/approaches.

Chapter 4.1 introduces a new, simple energy use metric that proposes to answer to some of the identified issues of the current approaches. First of all, the methodology is simple, replicable and based on readily available datasets accessible to every general end-user, including local governments. Moreover, the energy metric combines the consumption of both buildings and commute transport, assumed as the biggest energy demanding categories in cities and urban areas. Additionally, mapping the results from the metric at a large geographical scale provides new information about the spatial configuration of energy consumption in England by LSOA unit. This can also inform about energy efficiency by locating the highest per capita areas on which intervention strategies of efficiency improvement may be carried out.

Chapter 4

Methodology: energy use metric, urban form and their relationship

The focus of this thesis is to obtain a better understanding of the relationship between energy consumption and urban form to derive new information that can be used in energy planning and general urban planning at local scale. This information can then be used to promote sustainable development and more effective management of energy demand by reducing carbon-based energy consumption and mitigate well-known negative effects. Consequently, the methodological approach followed to achieve the main goal and presented in this chapter is split in three main stages: (i) introduction of a new, simple energy use metric to estimate energy consumption; (ii) selection a large of urban form variables from which land use typologies are derived; (iii) measure the actual relationship between energy consumption and urban form variables through correlation and scaling laws analyses at different geographical scales. The second stage can be further broken in two key tasks: (i) the selection of relevant physical and socio-demographic characteristics presumed to have an effect on energy use, based on the concept of urban form; (ii) the computation of land use typologies derived from those urban form variables carried out by a principal component analysis and a cluster analysis procedures.

The unique feature of the current work refers to the use of a large scale of analysis – LSOA level – rather than study the relationships at a city scale and so looking at the scaling over urban areas *within* cities, rather than *between* them. Therefore, this analysis enables the understanding of the internal dynamics of the urban areas to aid a more focused planning. By adjusting urban planning and by using a large geographic scale to study the internal dynamics of cities, it is assumed that a better detailed information about energy

consumption is obtained. A detailed explanation of each stages and respective tasks follows.

4.1 Energy use metric

As aforementioned, the first stage of the research is to develop a new, simple energy use metric that combines the energy consumption of buildings and transport. As it is unfeasible to measure the consumption of every building and vehicle of a neighbourhood or a city, a non-detailed energy estimate at large scale is obtained using readily available official data. This use of easily accessible data sources and the non-complex approach makes it replicable to other regions in response to a major issue identified in the literature about most current procedures. Furthermore, the energy use metric is designed as user-friendly to allow its use by planners and policymakers seeking as an initial consumption estimate of an area and, from there, outline strategies to reduce or mitigate carbon-related energy consumption. In a world seeking to reduce or mitigate CO₂ emissions and related energy, having a simple, accessible energy use metric and consumption estimates will equip planners, policymakers and any individual with background knowledge to draw actions to handle and manage those problems.

The energy metric was partly introduced in previous work (Osório et al. 2015, 2016, 2017*b*) and this chapter is mainly based on (Osório et al. 2017*a*). The method consists of: (i) data selection and aggregation at appropriate scale; (ii) the theoretical energy use metric framework; (iii) data output and presentation. An explanation of each step follows. Additionally, a detailed explanation of the downscaling procedure is presented in section 4.1.2.4.

4.1.1 Data aggregation, scaling and units

4.1.1.1 Data selection and aggregation

Energy consumption in urban areas arises primarily from buildings (here split into residential and non-residential buildings) and transport (including road and rail transport) (Anderson et al. 2015). The approach followed here to estimate the energy consumption of those two vectors includes only the operational energy of buildings, as this is immediately related to short-term urban characteristics that can interact with transport, and commute transport carbon footprint, converted to energy use. However, the flexibility of the procedure allows the future inclusion of other urban energy factors, such as the embodied energy of buildings or the transport of goods. The analysis of only the operational energy of buildings and

commute transport refers to the fact that these are urban components over which it is expected for local authorities and planners to have more influence to prompt short- and -medium-term changes. Policymaking of, for example, the road transport of goods and maritime transport into cities are subject to national policies that local governments can only try to influence.

To produce a simple energy metric enabling replication, available official datasets are used. The use of information published by official governing bodies in the UK is perceived as being both reliable and accessible data sources for end users of the research. However, the methodology is robust enough to allow the usage of other data sources of varying resolution, if available. Energy consumption values for buildings is derived from sub-regional energy utility data, a procedure found in some previous studies (Baynes & Bai 2009, Baynes et al. 2011, Lenzen & Peters 2010). The Department of Energy & Climate Change (DECC) is the main government institution in the UK publishing energy-related data. Consequently, energy consumption estimates for buildings are based on DECC's tables of sub-regional energy use. This is split by type of building (residential and non-residential) and form of energy (electricity, gas, etc.).

The analysis of transport energy consumption is restricted here to commute transport mainly because of: (i) the availability of reliable data; (ii) the significant proportion of energy consumption this commute transport represents (Boussauw & Witlox 2009, Muñiz & Galindo 2005) in urban areas – about 4.1% of total energy use and about 14.4% of transport energy use in the UK (Lovelace 2014); (iii) the greater influence (and control) that local governing bodies and planners have to produce actual changes in the system. Commute transport carbon footprint (then converted to energy use) values are derived from the Origin-Destination (OD) matrix table of work commute journeys published by the Office for National Statistics (ONS) and mapped by the DataShine web platform (O'Brien & UCL CASA 2014). The information of the OD table allows the calculation of estimates for each mode of transport (car, bus, etc.).

4.1.1.2 Defining scale, scaling and units

Urban energy use estimates depend on the spatial scale, i.e. how urban areas are delimited in space (Parshall et al. 2010), which depends on data availability (World Bank 2009). Nonetheless, urban boundaries are not always followed by the administrative change of city limits (Marcotullio et al. 2014, Tayyebi et al. 2011), and these administrative boundaries, in particular large cities, usually do not cover the whole urbanised area of a city. Moreover, different urban/rural classification systems will produce contrasting figures for energy con-

sumption, raising obstacles to planners and policymakers that have to generate strategies based on unreliable or biased energy estimates (Steinberger & Weisz 2013). In this work, urban boundaries are not defined to prevent deriving unreliable energy consumption estimates, but rather Lower layer Super Output Area (LSOA) geographical units (ONS – GCS 2011) are used that, at the same time, act as a proxy for large scale analysis. Simultaneously, this enables the understanding of the internal dynamics of cities and urbanised areas without having to pre-define them.

A LSOA is a geographical unit used for statistical purposes, defined as an area with 1000 to 3000 residents and from 400 to 1200 households (ONS 2011b). The use of a large scale of analysis enables a better focusing of strategies to modify energy demand, as it is more individual/household-oriented and allows more fine-grained control of the policies implemented by local governments. Regardless of the selected scale, the methodology may be applied at any level of analysis for which data is available, as the main feature of this procedure is combining both buildings and transport energy consumption (see Equation 4.2).

The use of LSOA units requires the application of a scaling procedure as much of the information used to compute the energy consumption estimates of buildings and transport is not available at LSOA level. Apart from the electricity and gas consumption of buildings (both residential and non-residential), DECC's information (data source for the remaining buildings energy sources) is published at Local Authority (LA) level. The ONS' OD travel to work matrix table (data source for the commute transport carbon footprint) is published for Middle layer Super Output Area (MSOA) units (a smaller scale than LSOA) (ONS 2011b).

Overcoming the problem of non-standardized energy statistics is carried out by using a *downscaling technique* (Wilby et al. 2004, Wilby & Wigley 1997, Wilby et al. 1998). Downscaling is commonly used in climate studies and climate projections (Imada et al. 2015, Kim et al. 1984, von Storch et al. 1993), as it allows establishing a relationship between coarse spatial resolution data and local-scale regions. The procedure followed here uses a scaling factor (detailed in section 4.1.2.4) to rescale the available data to LSOA resolution. The building's scaling factor is derived from the Generalised Land Use Data (GLUD) by LSOA published by the ONS and is based on the Ordnance Survey MasterMap[®] land features map (OS – MM 2017). These GLUD features assign a different land use to each land parcel of a LSOA unit. The use of outdated GLUD features (originally published in 2005) brings some limitations, such as not considering the latest densification and planning policy actions indicated, for example, in the NPPF (DCLG 2012). Additional shortcomings are related with the actual methodology to classify the Ordnance Survey MasterMap[®] land

features, such as domestic and non-domestic buildings. Considering that the classification is an automated procedure, a set of rules had to be adopted to define each land use feature, i.e. automatically classify the polygons of the Ordnance Survey MasterMap®. The limitations of the procedure were recognised and an updated 2006 version was produced (DCLG 2009), though not made available for the public (and later the product was discontinued by the Department for Communities and Local Government (DCLG)). However, the use of alternative datasets – for example, CORINE Land Cover (Büttner et al. 2004, EEA 2017) – with different resolutions (usually coarse resolutions) would present a problem (Moreira et al. 2016) as the energy use metric is arranged at LSOA scale. Therefore, the usage of GLUD features for the downscaling of the energy of buildings is regarded as reliable and producing consistent results.

As for transport, the commuting population from the Census dataset published by ONS is used as the scaling factor to convert the transport energy consumption from MSOA to LSOA geographic level. The use of commuting population instead of total population prevented including a bias into the downscaling procedure since, for example, the young population (less than 16 years old) is not included in the commuting population.

As mentioned, commute transport data is originally published at MSOA level: commute journeys by mode of travel are released for population-weighted MSOA centroids, thus giving the total number of people commuting between each OD MSOA centroid pair (shown in Figure 4-1). The data gathered here only used outbound flows, doubling these to obtain return-journey estimates. The following methods of travel are considered: train, bus/coach, motorbike/moped and car.

The transport carbon footprint is obtained to the distance between Origin and Destination of each commute trip and converted to energy use (Section 4.1.2.2 for more details). The downscaling technique is then applied to calculate the carbon footprint at LSOA scale of both road and rail transport from the MSOA data. The choice of the scaling factor, such as population density, total area, building footprint or other, is very important, since the scaling metric can give different results, leading to different insights in each case and by cross comparison (see Chapter 5).

To combine the energy consumption of buildings and the commute transport carbon footprint into the same framework, further action is required. DECC's datasets on the operational energy consumption of buildings – including the consumption of electricity, gas, coal and other products by both residential and non-residential buildings – are published in *kWh*, based on meter readings and hence are point-of-use energy figures (DBEIS 2017b). On the other hand, transport carbon footprint was originally obtained in kgCO_2 . Since the

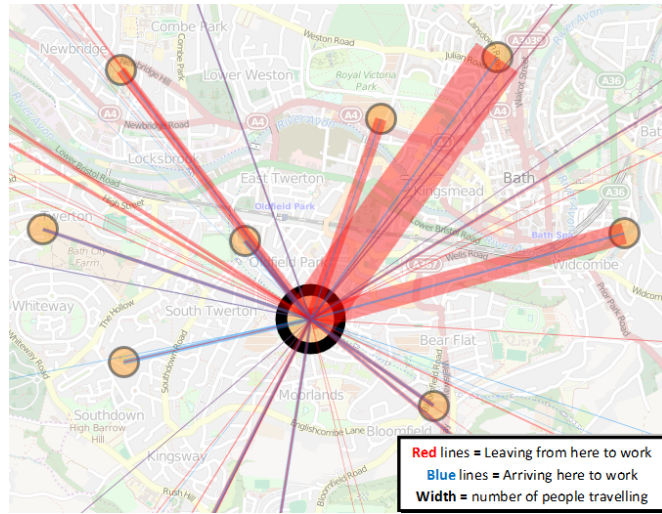


Figure 4-1: Origin-Destination travel to work flows in the Bath region (yellow circles show MSOA centroids and line thickness represents the number of people commuting). Source: DataShine (O'Brien & UCL CASA 2014).

energy metric used herein includes an estimate of both buildings and commute transport, the common SI unit of measurement the megajoule (MJ) is used. The conversion from kWh to MJ is based on the following rate:

$$1kWh = 3.6MJ \quad (4.1)$$

The conversion of buildings energy values is straightforward (given that source data is made available in kWh), but the conversion of the commute transport carbon footprint is mainly based on fuel conversion factors for each mode of transport and included several steps (detailed in Section 4.1.2.2). Overall, the introduced energy use metric combines the energy consumption of buildings and commute transport in MJ , allowing the understanding of the consumption at LSOA level and the internal and external dynamics of cities and general urban areas.

4.1.2 Energy use framework

The new, combined energy use metric approach introduced here is built on the fundamental relationship:

$$E = B + T \quad (4.2)$$

where E is the Total Energy Consumption, B is the Buildings operational Energy Consumption and T is the commute Transport carbon footprint converted to Energy.

The method produces a unified energy use metric to launch a more empirically-oriented and simple approach to the estimate of total energy use. Follows a description of the calculation of each energy vector.

4.1.2.1 Buildings: residential and non-residential

The sub-regional energy utility data for buildings published by DECC covers the main forms of energy: electricity, gas, coal, manufactured fuels, petroleum products and bioenergy & waste. With the exception of the latter form of energy, DECC's tables distinguishes each form of energy between domestic (i.e. *residential*) and industrial & commercial (here perceived as *non-residential*) buildings. Therefore, the integration of every factor is given by:

$$B = R + N + W, \quad (4.3)$$

where R is the energy consumption of Residential Buildings and N is that of Non-Residential Buildings and W is the value for Buildings' Bioenergy & Waste.

The energy consumption of residential buildings R results from households and essentially refers to the consumption of electricity and gas by families (Howard et al. 2012, Swan & Ugursal 2009). Based on the collected data published by DECC, that consumption can be described by:

$$R = R_e + R_g + R_c + R_m + R_p, \quad (4.4)$$

where R_e to R_p are the Residential consumption values for Electricity, Gas, Coal, Manufactured Fuels and Petroleum Products, respectively.

On the other hand, the energy consumption of non-residential buildings N results from public buildings, corporate offices, factories and other non-residential structures (Gaglia et al. 2007, Pérez-Lombard et al. 2008). The consumption of non-residential buildings is broken down in the same way as Equation 4.4.

4.1.2.1.1 Downscaling

A downscaling procedure is applied to adjust DECC's information for some sources (specifically coal, manufactured fuels and petroleum products) of energy consumption of buildings at LA geographic level LSOA. Using a scaling factor to estimate the values of each form of energy:

$$E_L = \frac{E_{LA} F_L}{F_{LA}}, \quad (4.5)$$

where E_L and E_{LA} are the Energy Consumption values by LSOA and LA, respectively, and F_L and F_{LA} are the Scaling Factor values by LSOA and LA, respectively. The actual values used for the scale factors F_{LA} and F_L depend on which metric is chosen to scale with.

As aforementioned, the scaling factor used here is based on the GLUD features published by the ONS and made available at LSOA geographic level. A more detailed explanation of the downscaling procedure can be found in Section 4.1.2.4. For residential buildings R , GLUD's category designated as "domestic buildings" (in m^2) is used as scaling factor, since it refers to the area covered by those type of buildings. As for non-residential buildings N , the land use classification designated "non-domestic buildings" (in m^2) is used as scaling factor. Consequently, the sum of the values of the two factors was used to compute the buildings' bioenergy & waste W consumption at LSOA. The use of the mentioned GLUD's land use categories refers to the fact that these features are directly associated with the estimated energy consumption of each type of building: residential and non-residential.

4.1.2.2 Transport: road and rail

Transport energy use is the other of the two major contributors to the total energy consumption (Hickman et al. 1999, Johansson et al. 2014). Here only commute land transport is considered, which primarily consists of road and rail transport (Rodrigue et al. 2013, Wang et al. 2014). According to that premise and the ONS' commute trips tables, the following is considered:

$$T = Ro + Ra, \quad (4.6)$$

where Ro is the Road Transport energy converted-Carbon Footprint and Ra is the Rail energy converted-Carbon Footprint.

Road transport consists of the transport of both passengers and goods on roads and its energy consumption is mainly derived from diesel and petrol (Delucchi 2003, Rodrigue et al. 2013). In this work only commute travel was taken into account. For road transport, ONS' data provides information about the number of people travelling by car, bus/coach and motorbike/moped. To obtain the carbon footprint (then converted to energy use in MJ) of commute transport, all outbound journeys by road and rail transport between every Origin-Destination (OD) MSOA centroid pair in England are considered. Therefore, the calculation of the road transport carbon footprint for any given mode of transport is obtained from:

$$Ro = LD_{OD}C_fPW_d2 \quad (4.7)$$

where L is the number of litres of fuel consumed by km, D_{OD} is the Road Distance between

an OD pair, C_f is the fuel conversion factor for each mode of transport, P is the number of people commuting by each method of travel, and W_d is the number of working days in UK in a given year; the factor of 2 is used to include the return journey of commuters each day.

The procedure for rail transport is similar to Equation 4.7, but instead of road distance D_{OD} the railway length between the closest train stations of each OD MSOA pair is considered. The distance (in km) between each OD pair (or train stations in the case of Ra) is obtained using a scripted interface to Google Maps on-line IDE tool (Google 2017). The fuel conversion factors for each mode of transport are based on recognised conversion tables (MacKay 2008), giving the values of commute transport consumption in kWh , which is then converted to MJ using Equation 4.1. Furthermore, it should be noted that, although some commute travels are made outside of the normal working week, it has been assumed that the contribution from this is small and thus only the number of working days W_d is taken into account. Finally, the sum of the values of Rail and Road carbon footprint converted to energy use gives the total Transport Energy Consumption T by LSOA.

The commuting journeys within the same MSOA units are also included in the analysis – a small component of at most 1% of the total. Since it is not possible to obtain the distance between the OD pairs of these trips, an approximation to the radius of each MSOA unit was taken as the commuting travel distance (assuming that each MSOA is roughly circular). From here, the transport energy consumption within each MSOA is obtained and downscaled to LSOA geographic level, and later added to the remaining transport consumption computed using Equation 4.7.

4.1.2.2.1 Downscaling

Similarly to buildings, a downscaling procedure is used to modify the original commute transport information from MSOA to LSOA geographic level. The commuting population at both MSOA and LSOA level published by ONS is used as the scaling factor. The procedure is similar to Equation 4.5, but replacing LA for MSOA values. A detailed explanation of the downscaling procedure is found in section 4.1.2.4.

4.1.2.3 Total energy consumption

The total energy consumption estimates given by Equation (4.2) at LSOA level are assumed to provide more detailed and further information to policymakers and urban planners seeking to reduce carbon-related energy demand without having to reduce growth or economic development (Alshehry & Belloumi 2015, Chen & Chen 2015, Kasman & Duman 2015).

Currently, most methods to estimate energy consumption rely on complex methodologies, using physically-based models (Anderson et al. 2015, Keirstead et al. 2012, Pfenninger et al. 2014) that require data from different sources with distinct quality criteria and uncertainty levels which may produce unreliable results. Additionally, a large number of those approaches are not integrative models and are applied to specific cities (or set of cities) (Allegrini et al. 2015, Anderson et al. 2015, Keirstead et al. 2012) and/or typologies of buildings or vehicles that generally are difficult to reproduce and replicate to different regions and scales.

Here is outlined a new energy use metric that follows a simpler and more empirically-oriented procedure which may be replicable to other regions. The simplicity of the introduced methodology relies on the usage of data published by official governing bodies, the premise of the relation between buildings and transport, and the application of simple scaling techniques.

4.1.2.4 Downscaling: issues and procedure

The selection of scaling factors is a complex process and past research has dealt with the many difficulties, problems and approaches (Di Luca et al. 2015, Leung et al. 2003, Lo et al. 2008, Salvi et al. 2016, Shukla & Lettenmaier 2013, Xue et al. 2007, 2014). In general, there is no perfect and standardized solution for statistical downscaling, since the process always implies making assumptions of how a given dataset at a coarse-resolution can be converted to larger scales. However, there are ways of minimizing the negative impacts of the downscaling procedure, such as using multiple linear regression to select the most appropriate scaling factors (Fumo & Biswas 2015, Mastrucci et al. 2014, Nouvel et al. 2015).

A regression procedure was performed by combining at least two independent variables, enabling the prediction of the energy consumption values as the dependent variable, i.e. buildings or transport energy. The selection of feasible independent variables was limited to data availability at MSOA and LSOA geographic level, including population, households,

total buildings footprint, surface area, among others. Multiple linear regression was thereby used to obtain the best fit to the energy consumption values at MSOA level. It was found that, for example, the commuting population driving a car or van and the residential buildings footprint gave a better prediction of the energy consumption of road commute transport than other choices: with the squared residuals $R^2 = 0.848$ (and $p < 0.005$). Other combinations – for example, total buildings footprint area and population (for transport energy) – explain less than 35% of the variability of the dependent variable. Accordingly, from the regression results and the comparison of the predicted values with the original estimated energy, the total buildings footprint and the commuting population by method of travel per OA unit were selected as the scaling factors to downscale the energy values of buildings and transport, respectively, from MSOA to LSOA geographic level. Therefore, the use of the selected scaling factors in this thesis is the best option considering the readily available data at both MSOA and LSOA scales and their significance for the energy of buildings and transport, respectively.

4.1.3 Data presentation

The introduced methodology uses large amounts of information. Therefore, a Geographical Information Systems (GIS) framework environment (ESRI 2001, Ormsby et al. 2010) is used to store and manage data, and map the results. GIS benefits multidisciplinary studies by allowing the integration of different source data (Reis 1996). It is also useful in planning and decision-making processes by favouring the identification of patterns and adding value to the analysed data (Longley et al. 2005). For example, the maps produced provide an important visualisation tool to recognise energy consumption patterns by sector, form of energy and mode of transport, as well as the geographic distribution of energy demand (see Chapter 5). The analysis of these patterns may then be employed to design better energy use mitigation strategies.

The geospatial data used here to produce the cartographic figures of the energy consumption is based on the information of the Geography Services made available by the ONS. This information is built from the boundary-line map created annually by the Ordnance Survey (ONS – GCS 2011). The use of an ArcGIS framework environment enabled the easy creation of maps showing energy consumption patterns by LSOA.

4.2 Urban form

Human settlements can be characterized by numerous metrics. The selection of these metrics or variables in this research is based on the concept of urban form and mainly focused on physical and socio-demographic characteristics. Urban form refers to the physical characteristics that compose the built environment, which include shape, size, density and arrangement of settlements (Clifton et al. 2008, Williams 2014). It can be studied at different scales – from regional to urban and street level –, and has significant impact on human activities (Schwarz 2010). Therefore, urban form influences social, environmental, economic and technological developments and, thus, also energy consumption (Creutzig et al. 2015).

Definitions of urban form vary in the literature (Schwarz 2010), but usually rely on landscape metrics (Huang et al. 2007, Schneider & Woodcock 2008, Bhatta 2010) and/or socio-economic indicators (Kasanko et al. 2006, Tsai 2005, Frenkel & Ashkenazi 2008). Landscape metrics are related to the physical structure of the city/urban areas (Herold et al. 2002, Huang et al. 2007), covering the analysis of land use change and quantifying urban sprawl (Dieleman & Wegener 2004). Essentially, these metrics describe the five main dimensions of urban form: complexity, compactness, heterogeneity, density and centrality (Herold et al. 2002, Huang et al. 2007). On the other hand, socio-economic metrics study those dimensions from the point of view of their impact on human behaviour (and vice-versa), i.e. by understanding the behaviour in space (Schirmer & Axhausen 2015). Thus, socio-economic indicators seek to include social processes into the analysis of urban form (Lima 2001), representing the built environment by the distribution of socio-economic variables (Schirmer & Axhausen 2015) and quantifying human behaviour.

Despite some empirical evidence about, for example, the link between transport fuel consumption and population density (Newman & Kenworthy 1989), there are no conclusive findings on the relationship between urban form and energy consumption (Makido et al. 2012). Research into this relationship is therefore crucial to tackle the current challenge of reducing carbon emissions and preventing their resulting consequences (Lovelace 2014, Anderson et al. 2015). The new insight about that relationship can then be used to obtain better planning, as urban form is also a means to expand social equity (Lima 2001) and achieve urban sustainability.

4.2.1 Selection of urban form metrics

The selection of urban form metrics for this research considered several definitions of urban form from previous studies (Schwarz 2010, Huang et al. 2007, Bhatta 2010, Kasanko et al. 2006, Schneider & Woodcock 2008, Tsai 2005). Considering the lack of a standard or accepted definition of urban form in the literature, which makes way to the use of a large number of indicators in previous studies, the selection of variables in this thesis had to assess their (i) presumed significance to the study of energy consumption, (ii) data availability and at the scale of analysis, i.e. for LSOA units, (iii) feasibility of the calculation and/or collection of the information. Furthermore, a selection of a large number of variables was favoured to (i) cover a wider scope of an urban form definition by including both landscape metrics and socio-economic indicators to better describe the characteristics of urban areas and cities, (ii) expand on previous research that usually is built upon a small number of variables. Additionally, as land use typologies are derived from the urban form dataset, the selection of landscape metrics is expected to provide information about urban sprawl, land use development, city size and urban land uses (Kasanko et al. 2006, Schneider & Woodcock 2008, Herold et al. 2002). On the other hand, the socio-economic indicators analyse compactness, density, intensification and population distribution (Burton 2002, Huang et al. 2007, Tsai 2005, Tratalos et al. 2007). Although some variables may be derived from others, the relationship established between them and energy consumption is distinct, justifying the use of each selected variable.

The following tables (4.1 and 4.2) lists the urban form variables used in this work, including their meaning, justification and/or purpose within the research's objectives, and example studies where the variables were used (if existing). It is important to notice that some selected variables are not found in previous studies (at least not directly), but they were deemed important in relation to the energy consumption, e.g. the road network which is directly associated with transport energy consumption.

Table 4.1: Selected urban form variables: landscape metrics.

VARIABLE	MEANING	JUSTIFICATION	REFERENCES
Perimeter of the geographical unit (m)	Total perimeter of each LSOA	Indicates raggedness and regularity	(Huang et al. 2007, Herold et al. 2002) (indirectly)
Surface area (km ²)	Total area extent of each LSOA	Illustrates area size; linked to energy efficiency	(Schneider & Woodcock 2008, Schwarz 2010)
Area of domestic buildings (m ²)	Surface area covered by residential buildings	Evidence for the sub/urbanisation, shows density of residential areas	(Tratalos et al. 2007, Burton 2002, Schwarz 2010) (indirectly)
Area of road network (m ²)	Surface area covered by the road network	Demonstrates compactness and complexity	LUT studies (Renner et al. 2014, Miller & Salvini 2001, Beckmann et al. 2007, Waddell & Ulfarsson 2004), usually indirectly
Road length (m)	Total extent lengthwise of the road network	Associated with accessibility	LUT studies (Renner et al. 2014, Miller & Salvini 2001, Beckmann et al. 2007, Waddell & Ulfarsson 2004), usually indirectly
Density of road length (m/prs.)	Total extent lengthwise of the road network per resident	Reveals accessibility and centrality	LUT studies (Renner et al. 2014, Miller & Salvini 2001, Beckmann et al. 2007, Waddell & Ulfarsson 2004), usually indirectly
Area of railway (m ²)	Surface area covered by railway	Demonstrates compactness and complexity	(none)
Extent of built-up area (m ²)	Surface area covered by built-up use, i.e. residential and non-residential buildings, road network and railway areas	Indicates urban area size	(Schwarz 2010) and input for various indicators
Proportion of built-up area (%)	Percentage of the area covered by built-up use in the total surface area	Linked to urbanisation degree	(Schwarz 2010, Kasanko et al. 2006) (mostly indirectly) and input for various indicators
Area of buildings (m ²)	Surface area covered by all buildings (residential and non-residential)	Evidence for the urbanisation, shows density of buildings	(Burton 2002, Tratalos et al. 2007, Schwarz 2010)
Proportion of area of buildings (%)	Percentage of the area covered by all buildings in the total surface area	Demonstrates compactness and density	(Burton 2002, Kasanko et al. 2006, Tratalos et al. 2007) (indirectly)
Extent of non-built-up area (m ²)	Surface area covered by non-built-up use, i.e. excluding the area of residential and non-residential buildings, road network and railway	Linked to urbanisation degree	(Huang et al. 2007) (indirectly)
Ratio of open space	Surface area of non-built-up use per surface area of built-up use	Linked to urbanisation degree	(Huang et al. 2007, Schwarz 2010)
Proportion of detached dwellings (%)	Percentage of detached dwellings in the total dwellings	Information on settlement structure and heterogeneity	(Tratalos et al. 2007)
Proportion of semi-detached dwellings (%)	Percentage of semi-detached dwellings in the total dwellings	Information on settlement structure and heterogeneity	(Tratalos et al. 2007)
Green space (m ²)	Area covered by green space, i.e. domestic gardens and greenspace in built-up areas	Related to both compactness and heterogeneity	(none)

Table 4.2: Selected urban form variables: socio-economic indicators.

VARIABLE	MEANING	JUSTIFICATION	REFERENCES
Resident population (prs.)	Number of usual residents	Indicates population size	(Tsai 2005, Schwarz 2010)
Male resident population ratio (prs.)	Number of male residents per female residents	Reveals gender influence on energy; linked to behaviour	(Elnakat et al. 2016)
Population density (prs./km ²)	Number of usual residents per km ² of surface area	Describes density and compactness	(Huang et al. 2007, Schwarz 2010, Elnakat et al. 2016)
Population density in built-up area (prs./km ²)	Number of usual residents only per unit built-up area	Describes density and compactness (within a specific area)	(Burton 2002, Tratalos et al. 2007, Tsai 2005)
Number of dwellings (dwg)	Total number of dwellings	Related to population size; indirectly linked to behaviour	(Tsai 2005, Schwarz 2010) (indirectly)
Density of dwellings (dwg/km ²)	Number of dwellings per unit surface area	Illustrates the density dimension of the urban form	(Burton 2002, Tratalos et al. 2007) (indirectly)
Number of household spaces (hh)	Total number of household spaces	Related to population size; indirectly linked to behaviour	(Tsai 2005, Schwarz 2010) (indirectly)
Density of household spaces (hh/km ²)	Density of housing, i.e. number of household spaces per unit surface area	Illustrates the density dimension of the urban form	(Burton 2002, Tratalos et al. 2007, Schwarz 2010)
Density of household spaces in built-up area (hh/km ²)	Density of housing in built-up area, i.e. number of household spaces only per km ² of built-up area	Illustrates the density dimension of the urban form (within a specific area)	(Burton 2002, Schwarz 2010)
Private car availability per 1000 inhabitants (no./1000 prs.)	Number of cars in the households per 1000 residents	Associated with welfare and transport structure	(Huang et al. 2007, Schwarz 2010)
Proportion of population with higher education (%)	Percentage of population with a higher education degree	Demonstrates the influence of education on energy; linked to behaviour	(Tratalos et al. 2007, Schwarz 2010, Elnakat et al. 2016)
Proportion of population in employment (%)	Percentage of population aged 16 to 74 with a job	Information on the impact of job structure on energy	(Tsai 2005) (indirectly)
Proportion of population employed in services (%)	Percentage of population aged 16 to 74 with a job in the services sectors	Information on the impact of job structure on energy	(none)
Proportion of flats in commercial building (%)	Percentage of flats, maisonnettes or apartments located in non-residential buildings	Linked to the housing stock heterogeneity	(none)
Ratio of detached houses per flat	Number of detached houses by the total number of flats, maisonnettes or apartments	Linked to the housing stock heterogeneity	(Burton 2002, Tratalos et al. 2007) (indirectly)
Yearly household income (£)	Household earnings in a year	Evidence for economic welfare	(Huang et al. 2007, Elnakat et al. 2016, Schwarz 2010)

As mentioned before, a large number of variables was selected to better describe the characteristics of urban areas. The urban physical structure is presented by the landscape metrics in such variables as *road length* and *proportion of built-up area*. The human behaviour is covered by the socio-economic indicators, such as *male resident population ratio* and *proportion of population with higher education*. Furthermore, employment in services include: Wholesale and Retail Trade; Information and Communication; Financial and Insurance Activities; and Human Health and Social Work Activities, which show the largest percentage prevalence of businesses in urban areas (Pateman 2011).

Socio-economic indicators are obtained from Census statistics (ONS 2011a) and landscape variables from land use (OS – MM 2017) and road network (OS 2017) datasets. However, the methodological approach used here allows adding other variables to the analysis if the data is available and results relevant to understanding the relationship between energy consumption and urban form. Moreover, data is compiled at LSOA geographic level so it can be compared with energy values.

4.3 Identifying land use typologies

Urbanisation has greatly changed land use patterns across the world and produced numerous and profound effects (Wu et al. 2011, Liu, He & Wu 2016). These effects include such as impacts on biodiversity, ecosystem functioning, regional sustainability and services beyond the city limits (Wu et al. 2011, Liu, He & Wu 2016). However, urban growth is not a continuous and a similar process in every place of the world: each city, metropolitan city, mega-city and others develop on their own pace, pattern and time-space, depending from the initial conditions and limitations (Wu et al. 2011, Bürgi et al. 2004). Urban dynamics result from various factors such as size, growth rate, form, population, etc., and that variability has direct and indirect impact on energy consumption and carbon footprint (Seto et al. 2010, Marcotullio et al. 2014, Czamanski & Broitman 2016).

One of the problems to study that variability is defining the boundaries of urban areas, as these change over time (Tayyebi et al. 2011, Marcotullio et al. 2014) and are not standardized. Administrative definitions do not properly outline urban spaces which creates obstacles to planners and policymakers. At the same time, it is important to recognize the different types of urbanized areas and land use types, from core to suburban and periphery, to understand their energy use (Marcotullio et al. 2014, Steinberger & Weisz 2013) and design better focused actions to reduce carbon-related energy consumption. In this work, a large scale geographical unit (LSOA) of analysis is used to avoid boundary definitions that

may introduce inconsistent results. Additionally, the selected urban form variables are used to identify land use typologies, so that the relationship between these area types and the energy consumption given by the energy metric can be understood. Simultaneously, the analysis provides information about the urban development of England by identifying the contrasting urban/rural land use throughout the country.

4.3.1 Principal component analysis

The analysis of a large number of variables and respective observations requires the use of different statistical techniques to facilitate the interpretation of the results. This because a big dataset may result in collinearity or multicollinearity effects, when two or more variables measure the same (or similar) attributes or subjects (Dohoo et al. 1997, Kock & Lynn 2012). Those effects are the consequence of the correlation between multiple variables and generate redundancy, i.e. variables that describe or explain the same phenomenon (Dohoo et al. 1997, Kock & Lynn 2012). In order to get rid of that redundancy and prevent it from influencing the results, such as incorrect correlation estimates and unstable regression coefficients (Dohoo et al. 1997), diverse techniques can be applied.

From the major available techniques to deal with redundant variables (or the probability of that happening), the principal component analysis (PCA) is considered the more psychometrically sound and mathematically simple (Stevens 2009, Pallant 2016). As a standard approach, this factor analysis technique is also able to perform an empirical summary of the dataset (Pallant 2016, Tabachnick & Fidell 2013). The simplicity of PCA and the straightforward objectives of this work – to identify land use typologies – are important advantages leading to this choice. These benefits are mentioned by others authors (Stevens 2009, Pallant 2016).

Functionally, PCA is an empirical variable reduction approach that specifies how a set of variables cluster together (Stevens 2009), helping to determine the number of dimensions of the dataset. The method can resolve multicollinearity by transforming correlated variables into a set of uncorrelated variables (called the components or dimensions) (Dohoo et al. 1997, Stevens 2009). The variability in the pattern of those correlations are obtained through the linear combination of the original variables (the factors) (Stevens 2009, Pallant 2016). Finally, the results generated allow the combination of similar variables according to their associated eigenvalue (i.e. the value of a vector whose direction is unchanged when a linear transformation is applied), eliminating redundancy.

4.3.1.1 PCA methodology

A principal component analysis (PCA) is used in this research to reduce the number of variables related to urban form. This 'cleaning' of the initial dataset later benefits the cluster analysis, as variable redundancy is removed. The R Studio free and open-source IDE software (based on the R language) (R Studio, Inc. 2017) is used to perform the analysis.

The whole number of urban form variables are considered for the PCA, both landscape and socio-economic variables, thus using a large scope of elements to characterize land use. From the different parameters available to perform PCA, a varimax rotation was selected. This orthogonal (rigid) rotation guarantees that the resulting variables (components) are uncorrelated, meaning that each component represents a small number of the original variables (Stevens 2009, Abdi 2003). This helps to reduce the collinearity and to explain the outcomes, since each original variable is usually associated with a small number of components (Abdi 2003).

Additionally to the rotation option, two extraction modes are used: (i) the eigenvalue rule (also known as Kaiser's criterion); and (ii) the scree test (or plot). The extraction mode allows the determination of the number of components to take from the initial dataset. The Kaiser's criterion declares that only the components associated with eigenvalues of 1 or more should be considered, as a component's eigenvalue describes its total variance (Dohoo et al. 1997, Pallant 2016). This criterion is a common, simple and objective 'rule of thumb' procedure to select the components explaining the variance of the dataset (Stevens 2009, Fabrigar et al. 1999). Although some problems about the application of this approach have been identified (Stevens 2009, Fabrigar et al. 1999, Hayton et al. 2004), it was also found that Kaiser's criterion is fairly accurate to identify the number of components when the number of the original variables is moderate to large (as in this thesis) (Dohoo et al. 1997, Stevens 2009). Moreover, previous research states that no single extraction mode is ideal and the interpretation of the results is mainly subjective, and thus the best approach is combining the information from different modes (Stevens 2009, Fabrigar et al. 1999, Hayton et al. 2004).

Consequently, to enhance the results of the Kaiser's criterion, the scree test is also applied. This test is based on the plotting of the eigenvalues of each component (Pallant 2016, Hayton et al. 2004). The rule to interpret the scree plot is to maintain all factors above the break point of the line representing the eigenvalues. This scree test is favoured by larger datasets to deliver satisfactory results (Hayton et al. 2004), though having a subjective interpretation.

The use of two extraction mode outputs in this work to select the optimal number of components describing the dataset of urban form variables is generally assumed as the more sensible strategy to obtain more reliable results (Fabrigar et al. 1999). Furthermore, the analysis of the rotated component matrix table also helps to identify the variables assigned to each component by looking over their respective eigenvalues and the total variance explained by each (and total).

4.3.2 Cluster analysis

Cluster analysis is one of the most popular techniques to sort and organize objects into subsets or clusters (groups). This classification method follows a numerical approach, using the degree of similarity (or dissimilarity) between each object, mostly based on the Euclidean distances of the individual objects (Everitt et al. 2011, Hastie et al. 2008), to create groups. Clusters are thus formed considering the homogeneity of its objects, i.e. the proximity among objects, and the separation or dissimilarity of the different groups: similar objects tend to be included in the same cluster; distinct items are incorporated in different groups (Everitt et al. 2011, Hastie et al. 2008). Resemblance and dissimilarity are key ideas when allocating objects to a specific cluster: the objects belonging to one cluster should be very different from the objects of another cluster.

Two main types of clustering are used: hierarchical and partitional (Jain & Dubes 1988, Anderberg 1973). In this work, both are used depending on the different objectives of each task. Hierarchical clustering does not define the number of groups in one single step: partitions take place from the total number of individual objects up until the whole dataset, i.e. from less to more inclusive clusters (Everitt et al. 2011, Anderberg 1973). The process always begins from the correlation matrix and each object is assigned to a cluster at each sequential step, depending of their inter-correlation (Bridges 1966). The correlation matrix is a table showing correlation coefficients between sets of variables, allowing the identification of which variable pairs have the highest correlation. Therefore, assigning each object to one cluster depends of the correlation established between objects within the same cluster. Graphically, hierarchical clustering can be represented by tree-like diagrams called dendrograms (Steinbach et al. 2000a), which are useful for visualization and analysis (for example Figure 4-2).

The main advantage of hierarchical clustering is that there is no need to state the number of clusters (groups) in advance. Furthermore, dendrograms enable a better understanding of the links between clusters and among each individual object (Bridges 1966). However, by breaking up datasets in levels of clustering, it is difficult to identify the optimal number

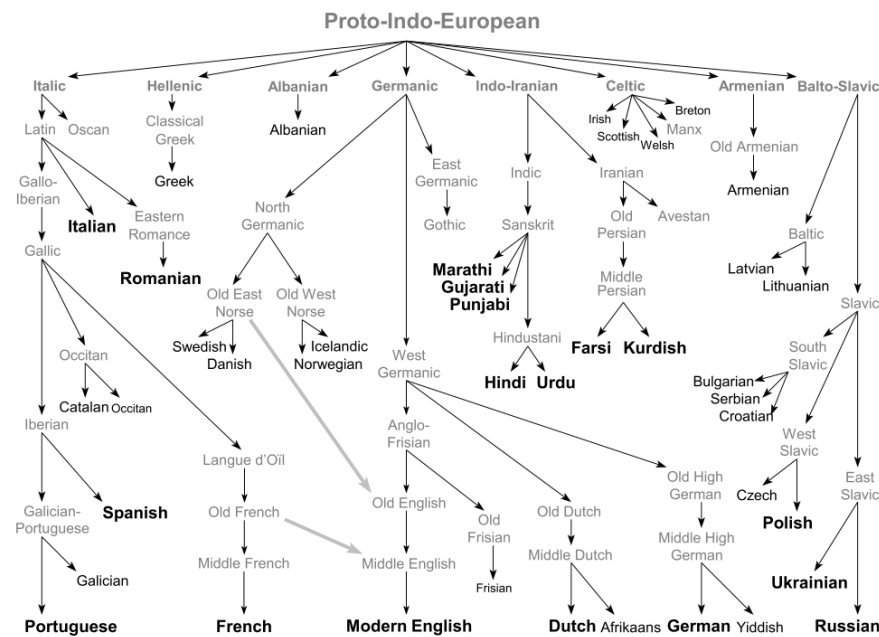


Figure 4-2: Tree-like dendrogram of the Indo-European languages showing the degree of similarity between each one. For example, Modern English shares a common origin to German and even Yiddish. Source: Lynch (Lynch 2017).

of clusters – i.e. the level which clustering should be split – and requires more computational time to process (Tarabalka et al. 2009) as the distances between each object is calculated. Accordingly, the use of dendrograms is important to find the clustering optimal level, although the interpretation of results may be subjective. On that account, hierarchical clustering is generally used as the first step of the clustering process – for example, to find outliers –, being followed by a better performing partitional clustering such as k-means clustering (Steinbach et al. 2000b). Outliers here refer to objects (values) of a dataset showing more dissimilarity to other objects, i.e. display higher Euclidean distance from the remaining objects of the set.

Partitional clustering contrasts with hierarchical approaches since it splits datasets into a predetermined number of clusters (Hastie et al. 2008, Likas et al. 2003). These clusters are non-overlapping, non-hierarchical, and based on the dissimilarities of the individual objects. From the diverse partitional clustering techniques, the k-means algorithm is one of the most popular, standard and widely used (Arora et al. 2016). Mostly used for unsupervised machine learning tasks – i.e. classifying objects by inferring hidden patterns and not considering sample training data describing previous knowledge of the datasets (Hastie et al. 2008) –, k-means clustering is based on the notion that a cluster can be represented by a central point: each object is assigned to the closest cluster centre (Steinbach et al.

2000a, Ding & He 2004). This cluster centre changes while objects are being 'added' to the cluster, as the process begins with guesses of the cluster centres locations (Hastie et al. 2008, Kanungo et al. 2002). The proximity between each object and the cluster centre is measured by the squared Euclidean distance and can be based on different quantitative variables (or criteria) (Hastie et al. 2008, Likas et al. 2003).

The need to define the number of clusters in advance may be an important drawback of k-means clustering. The use of hierarchical clustering before performing k-means, as in this work, helps to select the number of appropriate clusters and preclude that drawback to generate more reliable and strong results. Furthermore, the simplicity and intuitive operation of k-means clustering makes it suitable to obtain and identify the main typologies of the land use from a heterogeneous dataset of urban form variables.

4.3.2.1 Clustering methodology

Cluster analysis has been applied by other authors (Kendig 1976, Saksena et al. 2014, Moreira et al. 2016, Zhou et al. 2014, Masucci et al. 2015) to identify land cover and land use typologies, but at different scales and with different results. For example, using coarse resolution data may limit the significance of the results for large planning strategies (Zhou et al. 2014) since the identified boundaries will indicate different land use typologies from the real world. Moreover, most previous research relies on the analysis of landscape metrics, neglecting the importance of socio-demographic variables in the definition of boundaries of urban areas. Here, the proposed analysis covers a large bulk of variables and uses LSOA units to represent large geographical scale.

R Studio was used to obtain both hierarchical and k-means clustering (R Studio, Inc. 2017). The hierarchical clustering is carried out first for the resulting data factors found by PCA, using Ward's method and considering the squared Euclidean distance (Ward Jr 1963, Burns & Burns 2008) between the values. Ward's method involves an agglomerative clustering algorithm that chooses the pair of clusters to merge based on the minimal increase of sum-of-squares (squared Euclidean distance) (Ward Jr 1963, Burns & Burns 2008). To select the appropriate number of clusters of the dataset, both the clustering coefficients and the resulting dendrogram were analysed.

For the dendrogram, the major splits of the tree-like plot were examined to identify the main clusters (branches). These splits can also be identified by looking into the heights value of each observation, i.e. the value where the split occurs. On the other hand, the clustering coefficients characterize the clustering structure of the dataset, revealing the significance

of the obtained clusters by estimating the degree of dissimilarity between objects in the different clusters and how close (similar) are within clusters (Ravasz & Barabási 2003). The analysis of the outputs allows also the identification of likely outliers – objects that do not belong to any of the big clusters. These outliers are the objects (LSOA units) of the dataset representing smaller branches (i.e. splits from the main branches), demonstrating higher degree of dissimilarity with the remaining observations or objects. The exclusion of these outliers from the analysis results in better outcomes, since they influence the arrangement of all clusters.

K-means clustering follows hierarchical clustering by considering the optimal number of clusters found on the latter. The clustering was computed for 10 iterations and the results were analysed to find out of the existence of outliers, as these can influence the final result. The exclusion of these outliers usually avoids inconsistent outcomes, and furthermore they can also distinguish a 'special' group that should be analysed by its own. In this research work, the identification of probable outliers mainly considered the results from the hierarchical clustering. Therefore, k-means clustering was performed for the dataset that excludes outlier objects or cases. Ultimately, the final results (clusters) from k-means clustering (plus the outliers identified with hierarchical clustering) are expected to define the land use typologies of England by LSOA unit.

4.4 Urban form, land use and energy consumption

As mentioned before, the relationship between urban form metrics, land use typologies and energy consumption is studied by calculating the correlation values between the datasets, as well as identifying the scaling exponents and regimes between them. This section provides an explanation of the theoretical and methodological framework of that analysis.

4.4.1 Correlation analysis

Correlation coefficients describe the positive or negative linear relationships between two datasets, meaning that the increase of values of a set is simultaneous with the other or, on the contrary, the rise of one set denotes the decrease of values of the other set (Walker 2010). Since the work by Newman and Kenworthy (Newman & Kenworthy 1989) and following research, it has been suggested that a negative correlation is established between population density and fuel transport consumption, indicating that higher densities have lower fuel consumption (Bagley & Mokhtarian 1999, van der Waals 2000). This has guided

policymakers and planners to promote the concept of the *compact city* (Clifton et al. 2008, Creutzig et al. 2015, Masson et al. 2014, Kellett 2015), encouraging high density and mixed land-use (see Section 2.3 for more details). However, that approach disregards the links established in the urban systems between cities and suburbs (or other cities/urbanised areas) (Handy et al. 2005, Mindali et al. 2004), and ignores the negative consequences resulting from compactness, such as overcrowding, noise and air pollution, increase of traffic congestion, and others (Steemers 2003, Burton 2000, Melia et al. 2011). It was found that every change influences the whole urban system, as a result of the interaction of location decisions by population and businesses (Hillier & Vaughan 2007, Bettencourt et al. 2007, Mindali et al. 2004, Batty & Marshall 2012). Although the 'compact city' concept and its application is still relevant to influence energy consumption and land use planning, additional options should also be considered (Boarnet & Sarmiento 1998, Crane & Crepeau 1998, Krizek 2003).

In this thesis, correlation is used to explain the relationship between energy consumption and different urban form metrics, but goes beyond previous studies (Newman & Kenworthy 1989, Handy et al. 2005, Mindali et al. 2004, Huang et al. 2008) that have taken into account a small number of variables (Nichols & Kockelman 2015) and have focused on entire cities (Newman & Kenworthy 1989) and not large scale analyses, as the present work proposes. Adjusting the planning to the urban systems and the use of large scale analysis to study the internal dynamics of cities and other urban areas should provide more detailed information about energy consumption. These new detailed insights may then be used to design better strategies that reduce or mitigate carbon-related energy consumption in urban areas. Therefore, by considering disaggregated sets of both urban form metrics and energy, and by using small geographic units (LSOAs) to study the relationship between those series, this work introduces a novel approach into the overall research.

4.4.1.1 Correlation methodology

The Pearson product-moment correlation is used in this research to quantify the relationship between the different urban form variables (and derived land use typologies) and energy consumption. Accordingly, the use of correlation allows measuring the influence of each urban form variable on energy consumption at a LSOA geographic level. The option for Pearson's correlation is due to its consistency as a powerful and parametric test (Walker 2010).

Considering the different value range of both datasets, correlations were obtained for logged data. This helps to more easily establish linear relationships between the set of values and

identify outliers. To expedite the whole process, and taking into account the large number of variables of both datasets, a scripted application was created to automatically (i) convert the information into logged data and (ii) calculate the correlation coefficients. The results of the correlation analysis are discussed in Chapter 5.

4.4.2 Scaling analysis

Cities and overall urban areas are complex systems resulting from intricate demographic, social, economic, cultural, geographical and political dynamics and constraints (Hillier & Vaughan 2007, Batty 2005, Arcaute et al. 2015, Wang 2015). Many theories and research have tried to understand those dynamics and the complexity of cities (Portugali et al. 2012, Jiang et al. 2012, Samet 2013), from which the application of scaling laws is an important example. Scaling law relationships have been mostly used at city scale, comparing urban areas against each other to understand how the increases and decreases of socio-economic characteristics (and others) correspond with city size (i.e. population) (Arcaute et al. 2015, Bettencourt 2013). Although most research has been focused on socio-economic variables (Arcaute et al. 2015, Bettencourt 2013, Alves et al. 2015, Gomez-Lievano et al. 2016), other studies look on transport characteristics and related energy consumption (Louf & Barthelemy 2014a, Oliveira et al. 2014, Rybski et al. 2016).

The analysis of scaling variations provides information about the inner composition of cities and the relation between the micro, meso and macro scales of urban spaces (Cottineau et al. 2016). This is done by quantifying the dependencies and variation of the different urban variables in relation to population. Therefore, these new insights offer planners important information about the dynamics of the urban systems, i.e. the influence of population on each urban variable, that can be used to outline better strategies towards a city's sustainable development (for example: actions to reduce carbon-related energy use).

The basic scaling technique makes use of an analogy of Kleiber's allometric scaling of metabolic rate (Kleiber 1947), relating the variation of urban characteristics to population (Cottineau et al. 2016), using a power-law relationship, determined by:

$$Y = tP^\beta \quad (4.8)$$

where Y is the Urban Characteristic, t is a (possibly time dependent) Constant, P is the total Population of a city and β is the Scaling Exponent.

Considering possible values for β , three scaling regimes are found in the literature:

1. the sublinear regime, $\beta < 1$, is associated with economies of scale, where increases in population require proportionally less infrastructure, etc.;
2. the linear regime, $\beta \approx 1$, is associated with human needs and suggesting a constant per capita Y quantity across the city;
3. the superlinear regime, $\beta > 1$, is associated with increased productivity per capita resulting from more social interactions (Bettencourt 2013, Cottineau et al. 2016).

Literature on scaling laws to cities shows contrasting results: no consensus of how or which urban variable(s) follow those laws (Arcaute et al. 2015, Louf & Barthelemy 2014b, Pumain et al. 2006, Gomez-Lievano et al. 2016), though differences between Europe and USA have been found (Arcaute et al. 2015, Bettencourt 2013, Oliveira et al. 2014). The lack of consensus is related to the definition of city, as different boundaries suggest different scaling exponent values and regimes (Rybski et al. 2016, Cottineau et al. 2016, Fragkias et al. 2013).

In this research, the scaling analysis is focused on LSOA units, avoiding the complexity of defining city boundaries. This uniquely allows the understanding of the internal dependencies of cities and general urban areas, rather than cities as a whole, i.e. a sealed entity. Furthermore, the analysis is focused on the relationship between energy consumption and different urban characteristics (and derived land use typologies) not only population size, as most previous research on scaling laws.

In this work, Y is replaced by energy consumption and P by the selected urban form variables to identify their corresponding scaling exponent β . However, this work goes beyond previous studies (Holden & Norland 2005, Ewing & Rong 2008, Tso & Guan 2014) by using a larger and more detailed scale of analysis.

4.4.2.1 Scaling methodology

To obtain the scaling law exponents of any power-law relationship in the data, the logarithm is taken of both sides of Equation 4.8, giving the linear relationship:

$$\log(Y) = \beta \log(P) + C \quad (4.9)$$

where Y is the Energy Consumption indicator, P is the Urban form Characteristic and β is the Scaling Exponent ($C = \log(t)$ is a possibly Constant offset).

A linear fit is then used to find the gradient β and determine the scaling relationship between

the two variables. Due to the large number of variables, Python scripts were created and used to speed-up the whole process, as well as to produce graphic outputs. Overall, the influence of urban form on energy is analysed by both scaling laws relationships and their associated correlation coefficients. See Chapter 5 for the discussion of the results.

Chapter 5

Results and analysis

The results presented in this Chapter consist essentially of: (i) application of the energy use metric; (ii) identification of the land use typologies; (iii) outcomes of the correlation and scaling laws analyses. The use of LSOA units enables a more detailed analysis of the dynamics of urban areas, as well as the comparison of the results between the energy metric and the other procedures.

5.1 Energy metric

The new, simple energy metric is applied to all LSOA units of England. This includes more than 32,000 units covering human settlements of different characteristics: urban, peri-urban and rural areas. Considering the arrangement of the energy metric, this can be expanded and applied to other regions using similar LSOA geographic level subdivision, e.g. Wales and Scotland, or even other countries if a similar geographic division and data sources are found.

Energy consumption of both buildings and commute transport is converted (and shown) in *MJ* and results from the application of the introduced energy use metric (Chapter 4.1). Considering the bulk of data collected, the following maps are generated using a Geographical Information System (GIS) framework to present the most important vectors of consumption and findings of the research.

5.1.1 Buildings

Figure 5-1 shows that the lower per capita energy consumption of buildings is found in major cities and urbanised areas. The exception are natural-protection areas such as the ones found in the South West region: e.g. Dartmoor National Park in Cornwall and the Cranborne Chase chalk plateau in the counties of Dorset, Hampshire and Wiltshire. Consequently, it is possible to identify the Greater London region, the reversed *L*-shaped axis Liverpool-Manchester-Leeds-Sheffield-Nottingham, the city of Birmingham and outskirts as Wolverhampton and Coventry, and a conurbation that mainly includes Newcastle upon Tyne, Sunderland, Durham and Middlesbrough.

Other smaller cities and urban areas can also be recognised with lower consumption values, such as Bristol, Portsmouth and others. The region of Greater London presents, overall, lower per capita energy consumption, but Central London and some transportation axes originating from there show high consumption values. This is probably due to the fact that those areas have, first, scattered population, and, second, are mostly occupied by businesses (in non-residential buildings) which demand high operational energy. However, the less energy efficient areas, i.e. LSOA units showing higher per capita energy consumption values, are predominantly observed in the North region where various national parks are located (e.g. Lake District, Yorkshire Dales and North York Moors National Parks). Furthermore, transition areas as part of the England-Wales boundary, and other likely rural areas throughout the country exhibit higher per capita energy consumption. This is essentially caused by the lower population density per geographical unit that increases the energy cost in each LSOA, corroborating the association between higher densities and better energy efficiency (Newman & Kenworthy 1989, Næss 2012).

Additional interesting findings are shown looking at the main forms of energy used by buildings – electricity and gas (Figures 5-2 and 5-3). The lower per capita consumption of electricity is mostly observed in main cities and urban areas, although, for example, Central London shows the opposite. However, there are fewer LSOA units displaying lower per capita consumption than in Figure 5-1 that refers to the total energy consumption of buildings. This means that other forms of energy have a bigger influence on the total buildings consumption than electricity. In fact, the collected data for this research reveals that electricity represents, in average, less than 23% of the total energy consumption of buildings, and gas accounts for more than 65% of the total. Figure 5-3 shows the importance of gas in the total energy consumption of buildings: though the majority of England's territory is placed in the lowest legend group, the consumption values are much higher than for electricity in Figure 5-2 – up until 18,000 against less than 6,100 MJ/pc. Nevertheless,

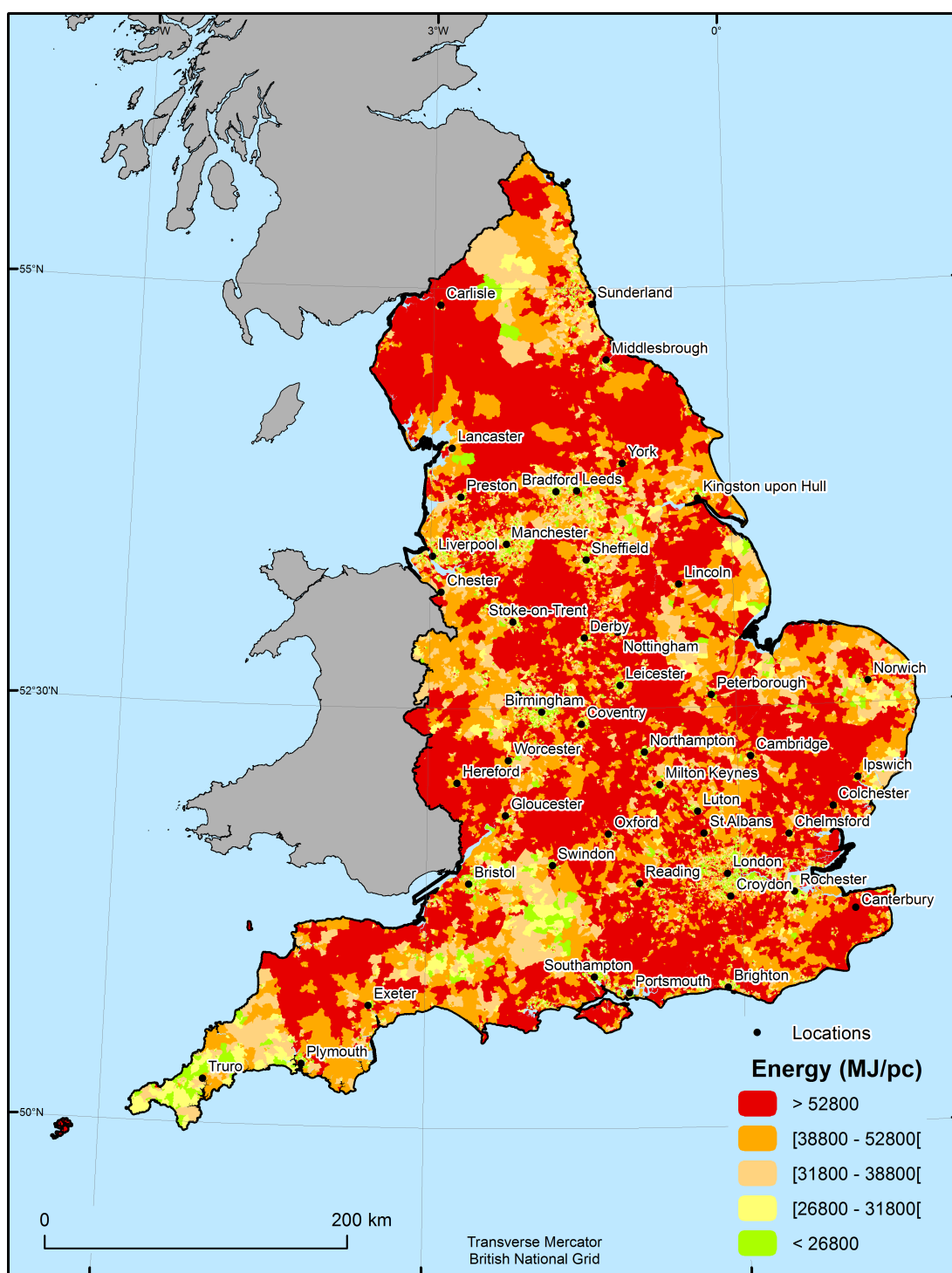


Figure 5-1: Energy consumption of buildings by LSOA per capita in England (2013). Based on: DECC (raw data); ONS (raw cartography) – Contains National Statistics data ©Crown copyright and database right [2011].

gas consumption by buildings is more energy efficient per capita than electricity. Moreover, as expected, the majority of energy consumption of buildings (more than 74%) refers to residential buildings.

5.1.2 Transport

Figure 5-4 shows that the lower transport energy costs are primarily found on the same areas identified in Figure 5-1: major cities and urbanised outskirts. However, Greater London region displays stronger energy efficiency for transport than for buildings, revealing the importance of its public transportation system.

The map of the total energy consumption of commute transport reveals some similarities to the previous (Figure 5-1), but the geographical dispersion area of the lower per capita values is smaller. In effect, it is mainly clustered around the main cities and high density urban areas, usually called suburbs. This reveals that the urban fringe areas, i.e. LSOA units from where people commute to work, are different from workplace locations (areas with lower per capita buildings energy consumption, as Central London). Besides Greater London, two significant examples of low per capita energy consumption of transport (compared to their buildings counterpart) are found in the Isle of Wight (the majority of the territory) and the Chester/Stoke-on-Trent axis in the South of Liverpool. These areas clearly show dormitory town characteristics (O'Donoghue et al. 2014, Hall & Tewdwr-Jones 2011, Rossignolo 2001), as workplace and home address are located in different areas, i.e. LSOA units. Other LSOAs also display dormitory characteristics and it is recognizable the shift from high per capita energy consumption of buildings (Figure 5-1) to low per capita transport energy use (Figure 5-4) all over England. Nonetheless, higher values of transport energy consumption are mostly found on rural and/or natural parks areas (these mostly in the North region), and so outside the main urban areas. The mapping of commute transport's energy allows also the better identification of peri-urban or urban transition areas than its buildings counterpart since these areas demonstrate higher per capita values for transport. This supports more effectively planners and policymakers to recognize the boundaries of cities that allow outlining more focused planning strategies based on land use typologies.

From the collected data it is found that the energy consumption of commute transport is, essentially, due to the consumption by car (more than 90% in average, though with exceptions, namely in the Greater London region). Policies to reduce this dependency of car must be put in place, as for example offering reliable alternative modes of travel. From a sustainability point of view, bus and train services are considered the best alternatives. Therefore, it is important to understand the supply of these services on commute transport

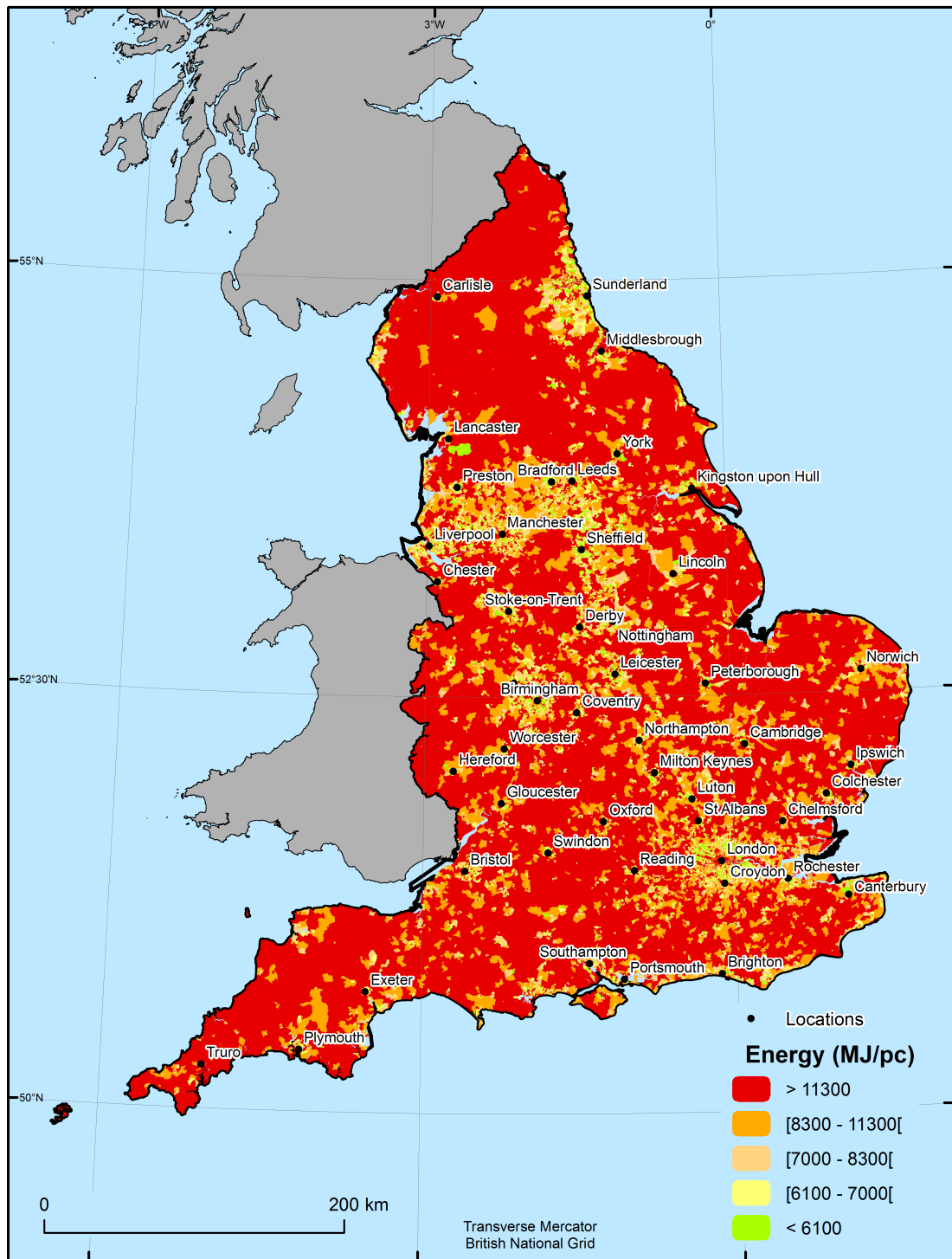


Figure 5-2: Electricity energy consumption of buildings by LSOA per capita in England (2013). Based on: DECC (raw data); ONS (raw cartography) – Contains National Statistics data ©Crown copyright and database right [2011].

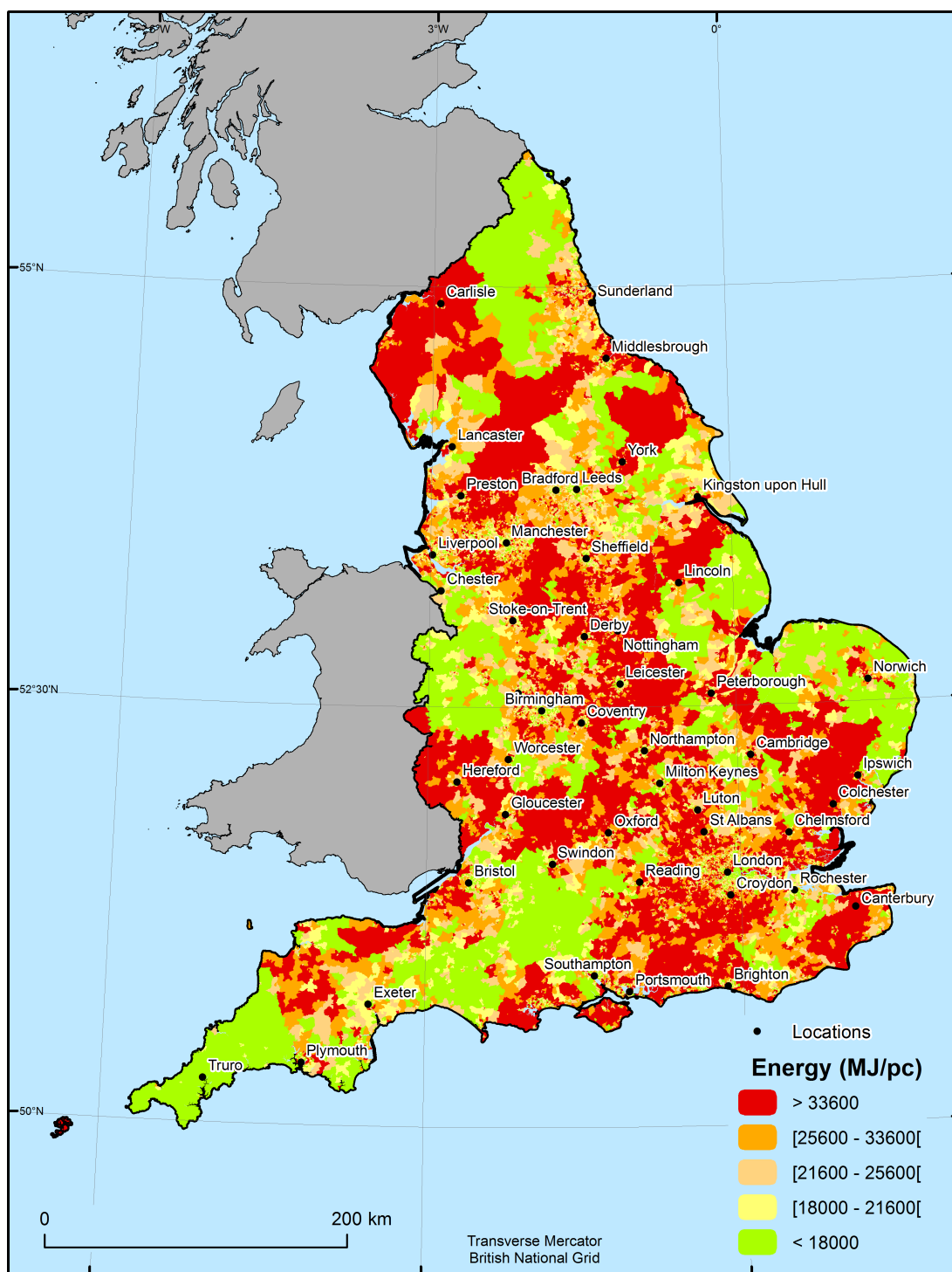


Figure 5-3: Gas energy consumption of buildings by LSOA per capita in England (2013). Based on: DECC (raw data); ONS (raw cartography) – Contains National Statistics data ©Crown copyright and database right [2011].

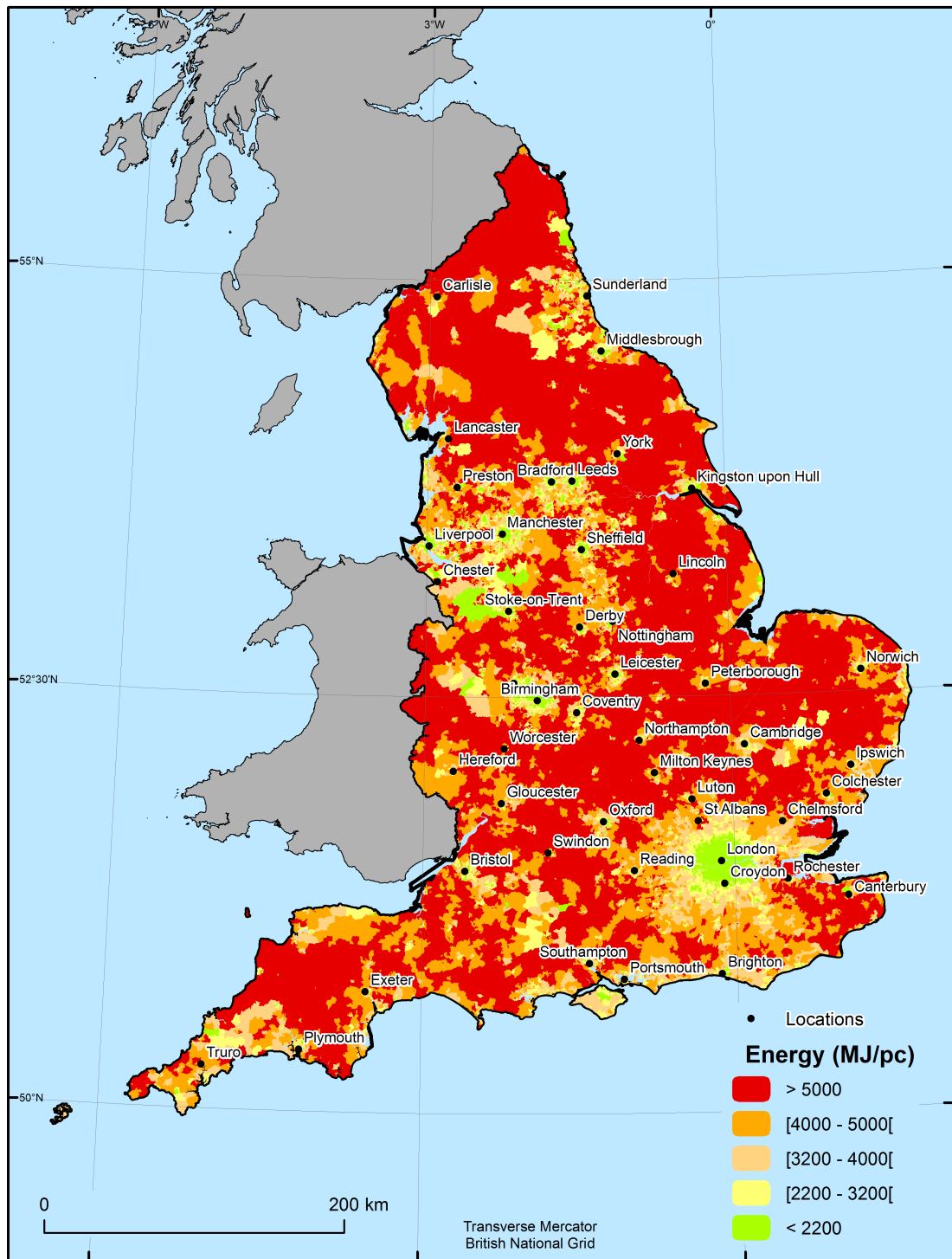


Figure 5-4: Energy consumption of commute transport by LSOA per capita in England (2011). Based on: ONS, DataShine (raw data); ONS (raw cartography) – Contains National Statistics data ©Crown copyright and database right [2011].

to identify problems and plan better solutions.

Figures 5-5 and 5-6 show the dispersal of bus and train energy consumption in England. The maps reveal a very energy efficient bus service (Figure 5-5) used to commute to work, as the majority of the LSOAs have low per capita energy consumption values, and a partially efficient train service (higher consumption values are found in the large South of England). However, despite this low per capita energy consumption of bus, and with a few exceptions as the outskirts of Central London and some mostly rural areas, the absolute values are very small when compared with the total commute transport energy use. Bus energy consumption accounts, in average, for less than 2% of the total transport energy consumption, and train a little more than 6%. It is possible to find exceptions to these average values, but the low energy consumption values demonstrated by those modes of travel and the related better energy efficiency, suggest that the improvement of those means of commute transport could encourage as an alternative to car use. Additionally, the high energy consumption per capita for train in the area around the Greater London region in the vast South England, show that: (i) this mode of travel is very important in the region as a means of commuting; (ii) the improvement of this service would result in better energy efficiency in other regions.

5.1.3 Total energy consumption

The important novelty of the energy use metric is the combination of the energy consumption of both buildings and commute transport at LSOA level. Figure 5-7 puts forth that unified metric, showing a significant similarity with the energy costs only for buildings (Figure 5-1). This is not unexpected since the average proportion of the buildings in the total energy consumption from the collected data is about 91%. However, there are many exceptions: some LSOAs have a proportion of more than 30% of commute transport in the total consumption. This reveals the influence of commute in areas such as some outskirts of big cities as Liverpool, Manchester and Sheffield, that demonstrate higher per capita total energy consumption values than buildings consumption (in Figure 5-1). The difference observed between the total energy consumption map and the ones for buildings and transport individually also validates the benefit and importance of having a combined approach, as given by Equation 4.2.

In general, the map for the total energy consumption (as the one for buildings consumption alone) shows that lower per capita values are observed in the major cities and urbanised areas, suggesting that these areas are more energy efficient (Makido et al. 2012, Amado et al. 2016). Comparing Figures 5-4 and 5-8 it is found how the more densely populated

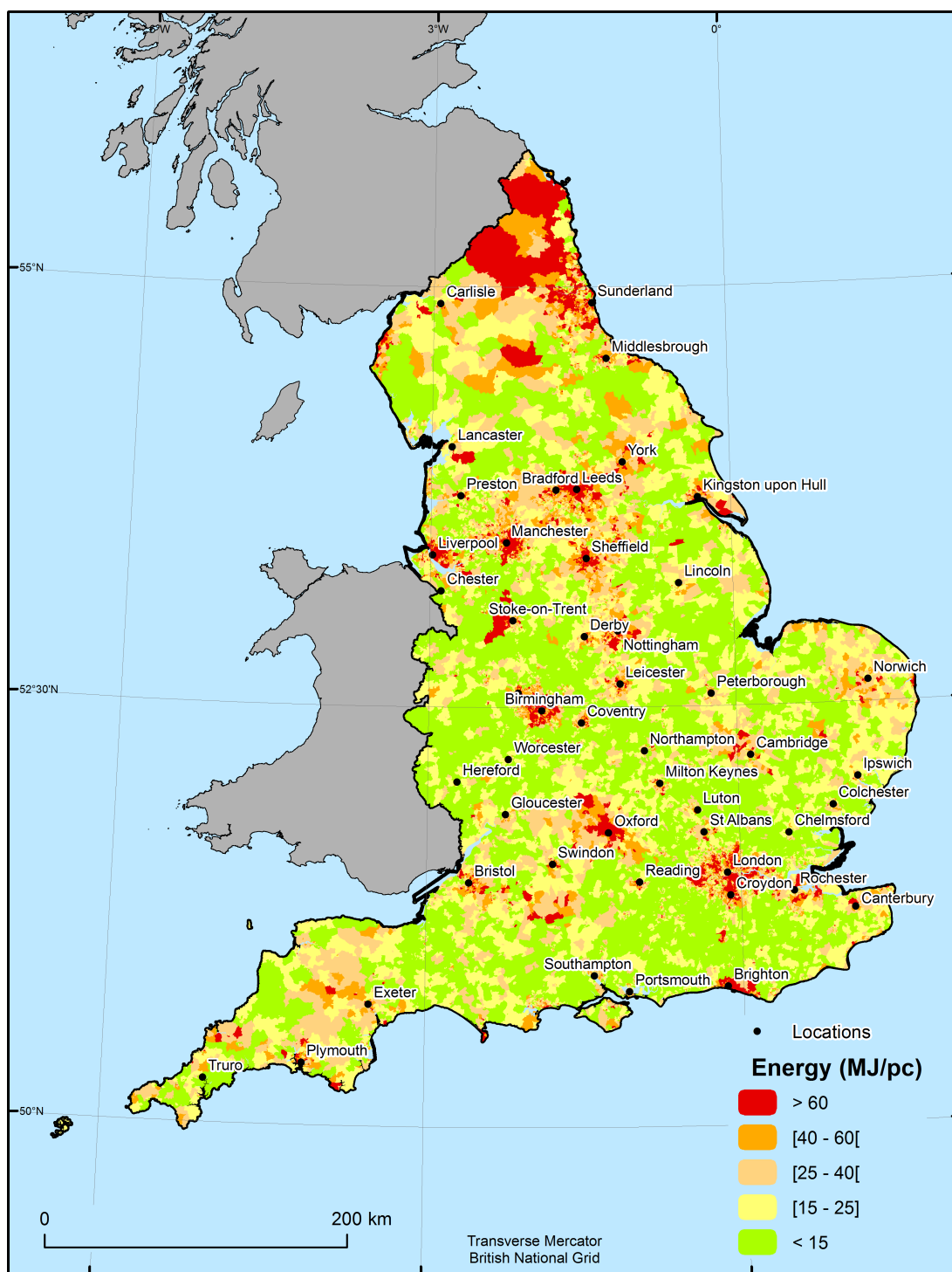


Figure 5-5: Commute bus energy consumption by LSOA per capita in England (2011). Based on: ONS, DataShine (raw data); ONS (raw cartography) – Contains National Statistics data ©Crown copyright and database right [2011].

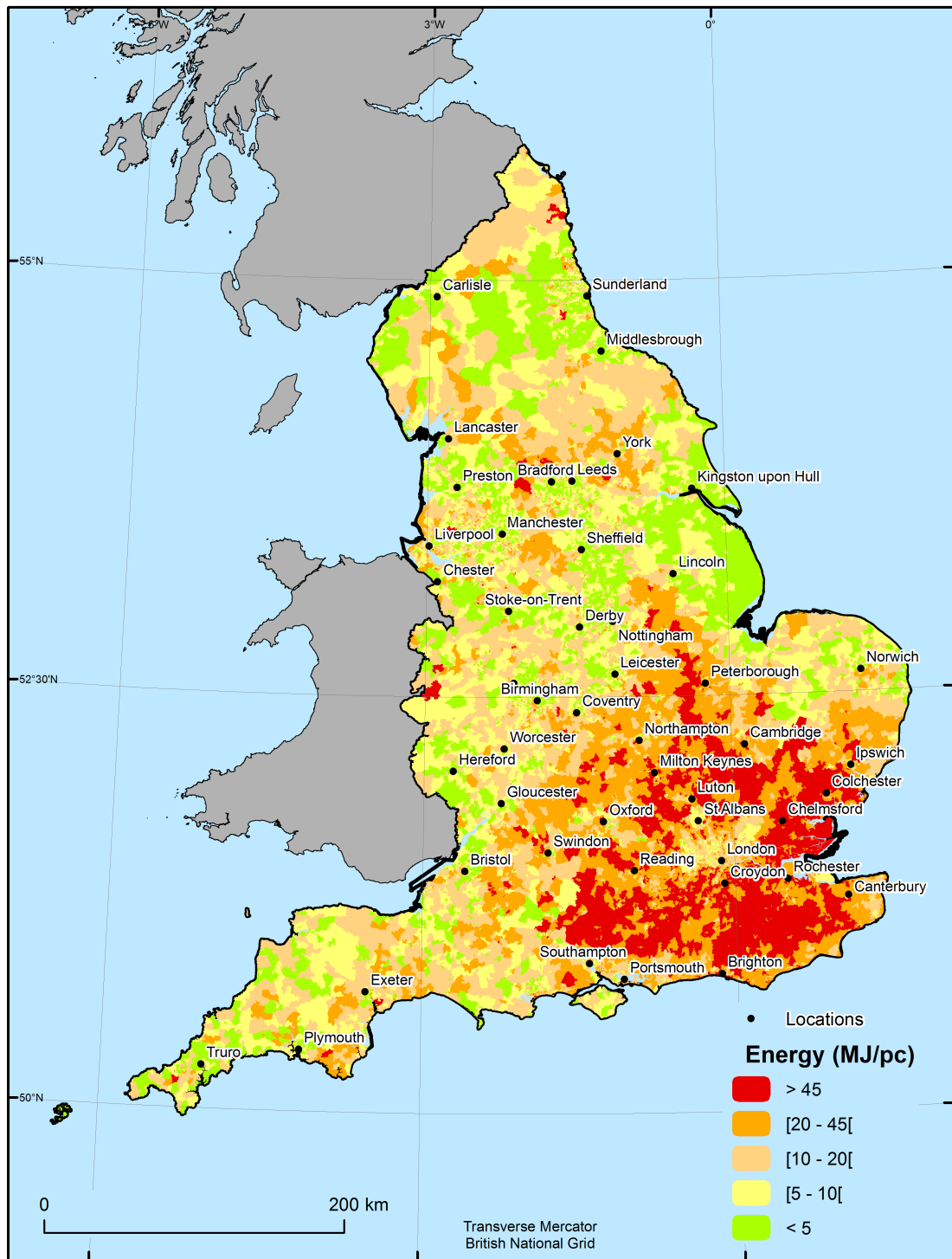


Figure 5-6: Train energy consumption by LSOA per capita in England (2011). Based on: ONS, DataShine (raw data); ONS (raw cartography) – Contains National Statistics data ©Crown copyright and database right [2011].

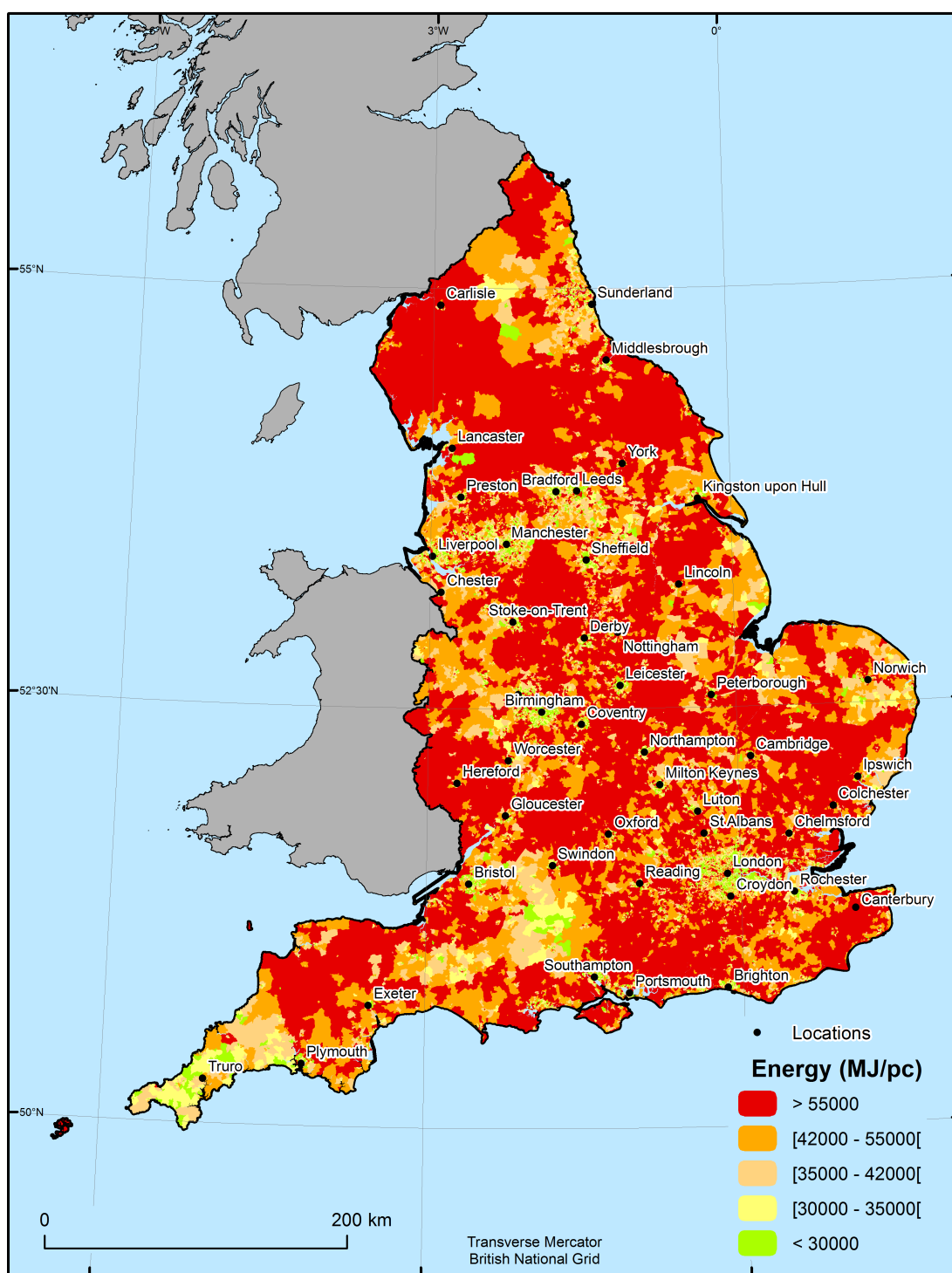


Figure 5-7: Total energy consumption by LSOA per capita in England (2013). Based on: DECC, ONS, DataShine (raw data); ONS (raw cartography) – Contains National Statistics data ©Crown copyright and database right [2011].

places correspond to the main centres of lower per capita commute transport energy consumption. This is clearer for the Greater London region, but also the Liverpool-Manchester region. Therefore, the maps indicate that higher population densities favour lower transport energy use, confirming previous research suggesting the compact city development to promote energy savings (Breheny 1995, Holden & Norland 2005, Newman & Kenworthy 1989, Næss 2012). As mentioned before (see Section 2.3), compact city may bring other problems, as the increase of air pollution or the depletion of resources, but this human perspective is out of the scope of this research.

The results from the application of the proposed energy use metric supports the assumption that population density is one of the crucial factors to influence the efficiency in cities and urban areas (Gudipudi et al. 2016), even if exerting more impact on transport than buildings. At the same time, this suggests per capita energy consumption as a satisfactory measure to compare against urban form metrics (in this case, the urban system in England). The analysis that follows (in section 5.3) seeks to confirm and further interrogate these findings, examining the relationship between energy consumption and urban form variables to obtain new useful knowledge that can be used to design better strategies to reduce energy use and related carbon emissions.

5.2 Land use typologies

The economic development and urbanization brought an increase of energy demand (Anderson et al. 2015, Lovelace 2014, Marcotullio et al. 2014). Considering that a significant proportion of the energy use is originated from fossil fuels bringing many negative consequences, mitigation measures are needed to reduce those impacts. However, implementing mitigation strategies requires the definition of the intervention areas, i.e. the definition of urban boundaries. These urban boundaries are constantly changing but administrative definitions are slow to follow (Marcotullio et al. 2014, Tayyebi et al. 2011). Furthermore, identifying urban boundaries is not an easy task as many areas present a land use mix transitioning between urban and rural space (Saksena et al. 2014, Moreira et al. 2016). The land use patterns across the world are not continuous and straightforward since the development of every city depends of various conditions and limitations (Wu et al. 2011, Bürgi et al. 2004). In the UK, defining city boundaries is even more problematic, as any town that received patent letters can be designated a city.

A large number of methods to define urban boundaries have been proposed (Saksena et al. 2014, Moreira et al. 2016, Burian et al. 2014, Zhou et al. 2014, Kendig 1976, Arcaute



Figure 5-8: Areas with high population density by LSOA in England (2011). Based on: ONS (raw data); ONS (raw cartography) – Contains National Statistics data ©Crown copyright and database right [2011].

et al. 2015, Masucci et al. 2015, Arcaute et al. 2016, Long 2016), but no definitive solution prevails over others. In the work presented here, a cluster analysis of the urban form variables (Tables 4.1 and 4.2) was applied to identify the land use typologies in England at a LSOA geographic level. Cluster analysis has been used by other authors (Kendig 1976, Saksena et al. 2014, Moreira et al. 2016, Zhou et al. 2014, Masucci et al. 2015) to define land cover or land use typologies. However, this research goes further by using a larger scale of analysis and examining the relationship of land use with energy. The cluster analysis technique offers a simple statistical approach that can be use and is at disposal of every planner and policymaker.

As with the energy use metric, the replication and simplicity of the method are essential premises to the selection of the procedure. Prior to the application of the cluster analysis, the urban form dataset is analysed and standardized using a Principal Components Analysis (PCA). This enables reducing the redundancy of the collected information, as well as to identify the data dimensions to be used on the cluster analysis. A discussion of the results of both the PCA and the cluster analysis follows, as well as the analysis of the obtained land use typologies.

5.2.1 PCA

More than 30 variables are used to characterize the urban form of each LSOA in this research (Tables 4.1 and 4.2). This results in a broader definition of urban form, but may also lead to the predictor variables being highly correlated and, thus, influencing the coefficient estimates of multiple regressions. Applying a Principal Component Analysis (PCA) mitigates that phenomenon (called collinearity), given its psychometrically sound and mathematically simple method (Stevens 2009, Pallant 2016).

PCA is a frequent and standard procedure and it is used in this research to identify the fundamental components or dimensions of the urban form dataset, later used in the cluster analysis. Identifying the optimal number of these dimensions or factors results from the analysis of three main outputs: (i) the scree plot; (ii) the rotated component matrix; and (iii) the variance of the variables.

The analysis of the scree plot or test (Figure 5-9) and the remaining outputs show that the characterization of the urban form at LSOA geographic level can be reduced to 6 dimensions. The scree test is a very useful to visual tool to identify the real dimensions of the dataset, even if its interpretation and, in general, of the PCA results is, often, subjective. Therefore, to justify the selection of the number (6) of the dimensions of the dataset, the

other outputs, as well as premises from previous studies are also considered and analysed.

Previous research (Guadagnoli & Velicer 1988, Osborne & Costello 2009, Bösehans & Walker 2016) refers that a factor should be considered reliable if the average value of its loadings is equal to or greater to 0.60, which is true to the 6 factors. Additionally, more than 68% of the variance of the extracted factors with eigenvalues equal to or greater to 1.00 (Dohoo et al. 1997, Pallant 2016) is explained by those 6 factors (see Table 5.1). Finally, the “rule of the elbow” of the scree plot is observed between 6 and 7 factors (Figure 5-9). This rule refers to a bend on the plot curve and a eigenvalue of, at least, 1.00 for the component. From that bend on, the remaining factors have relatively small significance and are all about the same size.

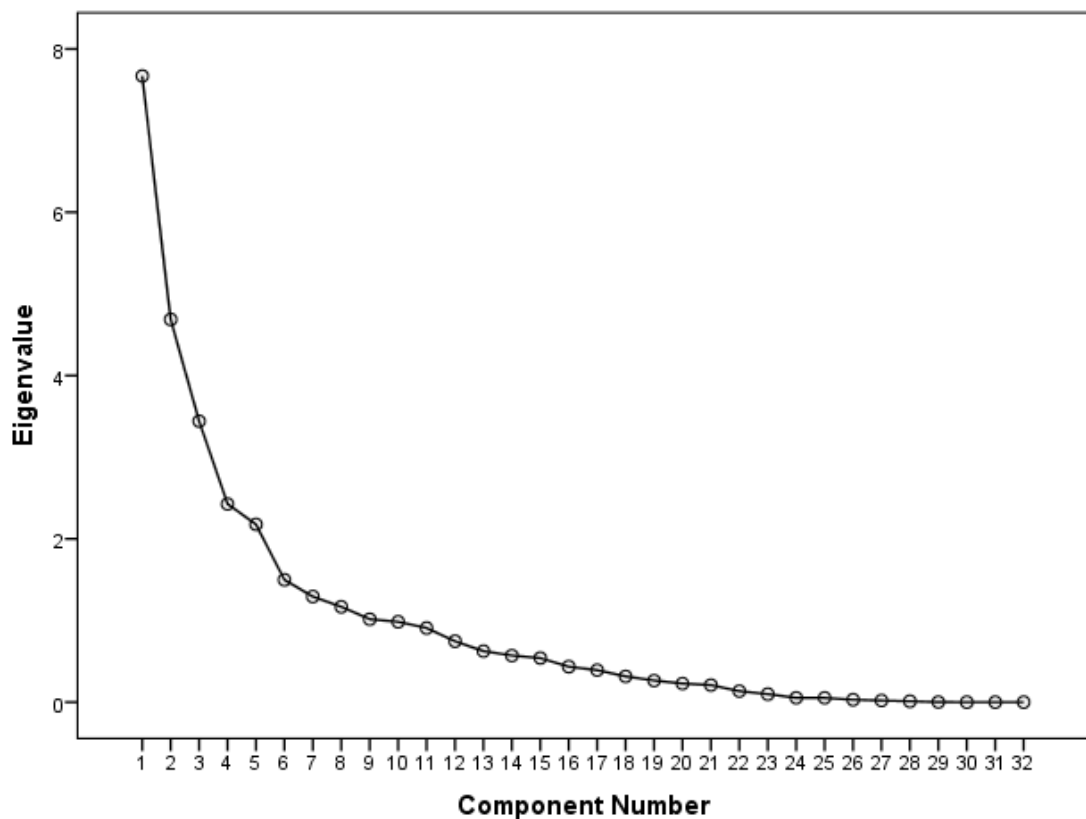


Figure 5-9: Scree plot for the PCA of the urban form variables showing a bend of the curve between 6 and 7 factors.

Concluding, the PCA suggests that no more than 6 are reliable factors, each including at least four variables (Table 5.1) with average loading above 0.60. This means that a large list of variables may not be needed for further studies examining the landscape and

socio-economic characteristics of a given area.

Table 5.1: Summary of the rotated factor solution for the PCA components. The labels of the selected components are based on the main variables that are included in each one.

COMPONENT	NUMBER OF VARIABLES	% OF VARIANCE	MAIN VARIABLES
1 "Area size"	6	23.97	Surface area (km ²) Extent of non-built-up area (m ²)
2 "Built-up area"	7	14.65	Extent of built-up area (m ²) Area of buildings (m ²)
3 "Density of housing"	6	10.75	Density of dwellings (dwg/km ²) Density of household spaces (hh/km ²)
4 "Housing"	4	7.58	Number of dwellings (dwg) Number of household spaces (hh)
5 "Socio-economic status"	4	6.81	Proportion of pop. with high education (%) Yearly household income (£)
6 "Population"	4	4.68	Resident population (prs.) Population density in built-up area (prs./km ²)

5.2.2 Clustering

In this work, two types of clustering are applied to determine land use typologies derived from urban form variables: (i) hierarchical and (ii) k-means. This is a common approach – hierarchical clustering followed by k-means clustering (Steinbach et al. 2000b) – because the latter requires the specification of the number of clusters (k) and the first enables to find the “ideal” or optimal number of a dataset.

5.2.2.1 Hierarchical clustering

Hierarchical clustering splits the original information into small groups based on the relationship between each object in a sequential procedure up until only each individual object remains. In this research, the significant PCA factors or data dimensions (6) were used to compute the hierarchical clustering instead of bulky original dataset. This allowed the (i) reduction of the computation time to process, but also the (ii) mitigation of the data redundancy and the likely collinearity. Two key graphical outputs of the hierarchical clustering are obtained to support the analysis of the results: (i) dendrogram, (ii) heights plot. Essentially, both describe the distances between each object and help to define the optimal number of clusters of the dataset to subsequently use on the k-means clustering. However, it is important to draw the attention to the fact that the interpretation of the results of hierarchical clustering is often subjective. And more for large datasets composed by diverse objects. To mitigate that subjectivity, and in the same way as with PCA, previous research guidelines and approaches were considered (Saksena et al. 2014, Moreira et al. 2016, Zhou

et al. 2014) to justify the options taken, leading to the final selection of the optimal number of clusters.

The resulting tree-like dendrogram (Figure 5-10) illustrating the disposition of clusters was analysed. This output shows a main split at height=68.58, preceded by two smaller splits (at height=115.70 and height=97.28) which refer only to 6 LSOA units. Looking up these 6 LSOAs on the heights plot (Figure 5-11), as well as locating them on a map – some units correspond to the Northumberland National Park, and so regarded as a segregated, special area –, it is suggested that these units are outlier values of the dataset, as they are detached from the remaining objects. Therefore, this small group was later excluded from the k-means clustering since it is regarded as an isolated cluster.



Figure 5-10: Tree-like dendrogram of the hierarchical clustering for the whole urban form dataset.

As mentioned, the main split in the dendrogram (Figure 5-10) is observed at height=68.58. The split distinguishes two branches: a dominant left branch and a smaller right branch. The right branch corresponds only to 828 LSOA units of the entire dataset (only about 2.5% of the total), which suggests that this set of elements may be considered an outlier cluster. This outlier order is recognized by analysing the location of the LSOAs. Identifying

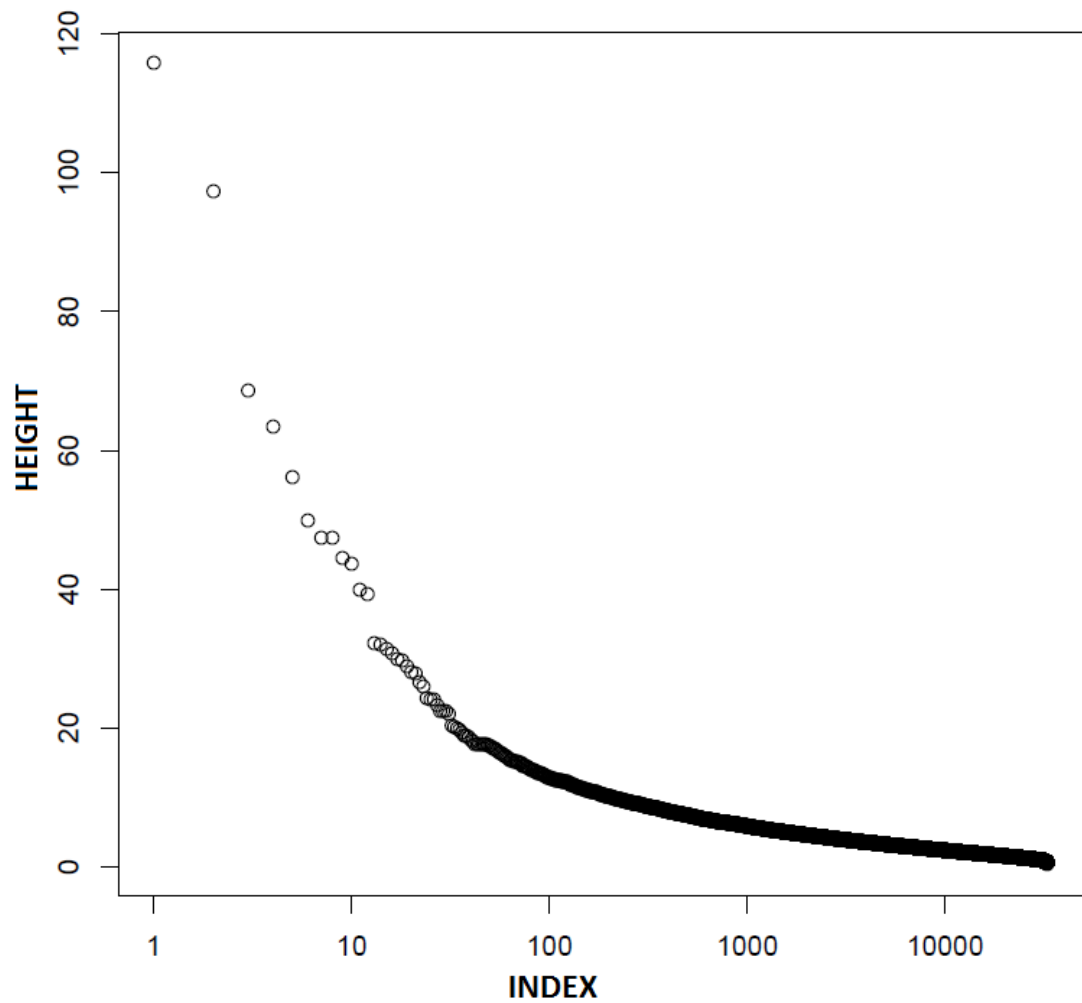


Figure 5-11: Heights plot of the hierarchical clustering for the whole urban form dataset. This plot shows the height value of every branch split.

this outlier set on a map reveals that it has a rural/urban mix land use, although essentially located in rural areas, and for that reason demonstrates mainly a transition perspective within the urban land use system of England. Moreover, the simple visual analysis of the right branch in the dendrogram shows that it is clearly set apart from the dominant left branch. Therefore, this distinction alone is strong enough to consider these 828 LSOAs as a different group. However, the dendrogram also shows that this outlier group of 828 LSOAs is distinct from the first outlier set of 6 LSOAs. Hence, though both are excluded, later, from the k-means clustering, these two outlier sets are also considered two different clusters.

Taking into account the new dataset excluding the two outlier groups, a second hierar-

chical cluster analysis was run. The dendrogram (Figure 5-12) shows two main splits at height=28.12 and height=27.93, preceded by (6) smaller subdivisions. This demonstrates that the dataset may be split in 7 or 8 major groups or clusters. On the other hand, the heights plot for this second hierarchical clustering (Figure 5-13) reveals many significant splits, as for example at: height=36.51, height=30.95, height=28.12, height=24.52 and height=22.78. If considering all these significant branches, the dataset could be split between 5 and 12 clusters. This would present two main issues: (i) an outcome of too much detail that would present difficulty to understand, opposing the simplicity purpose of this research; (ii) a resulting non-equivalent groups with those found in the dendrogram. Accordingly, it is considered that the optimal number of clusters of the dataset is 7 or 8, which are also identified the main divisions in the heights plot. These number of clusters were then tested using k-means clustering for the dataset excluding 834 LSOA units (referring to two outlier clusters).

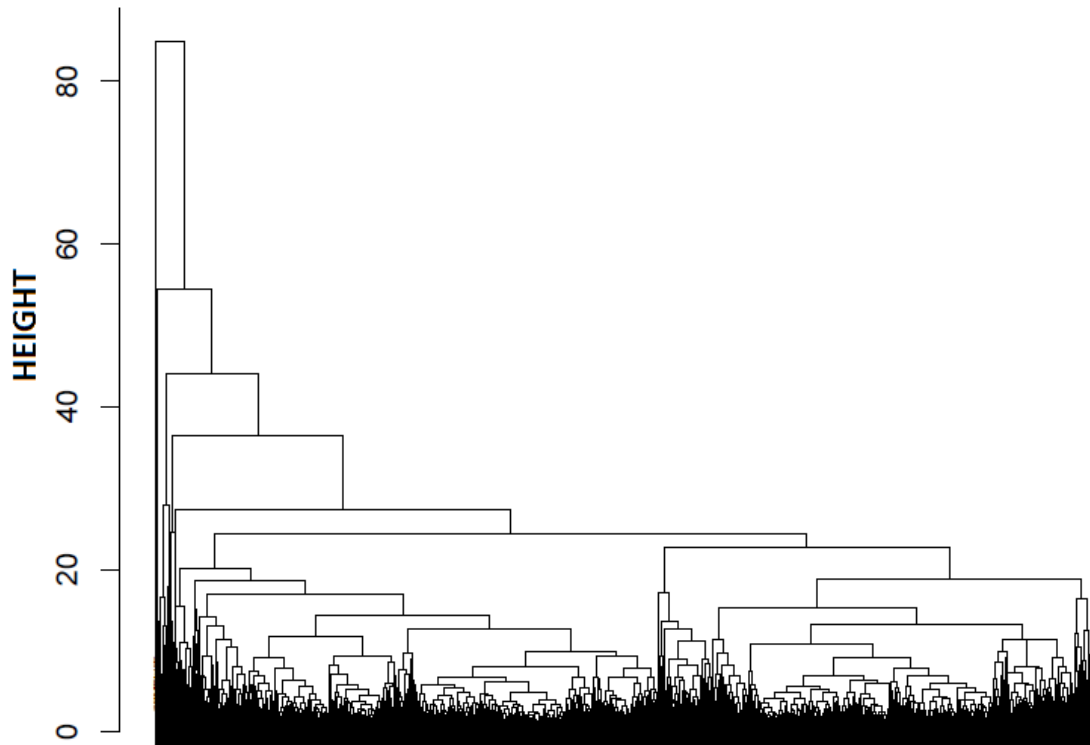


Figure 5-12: Tree-like dendrogram of the hierarchical clustering excluding the outliers of the urban form dataset.

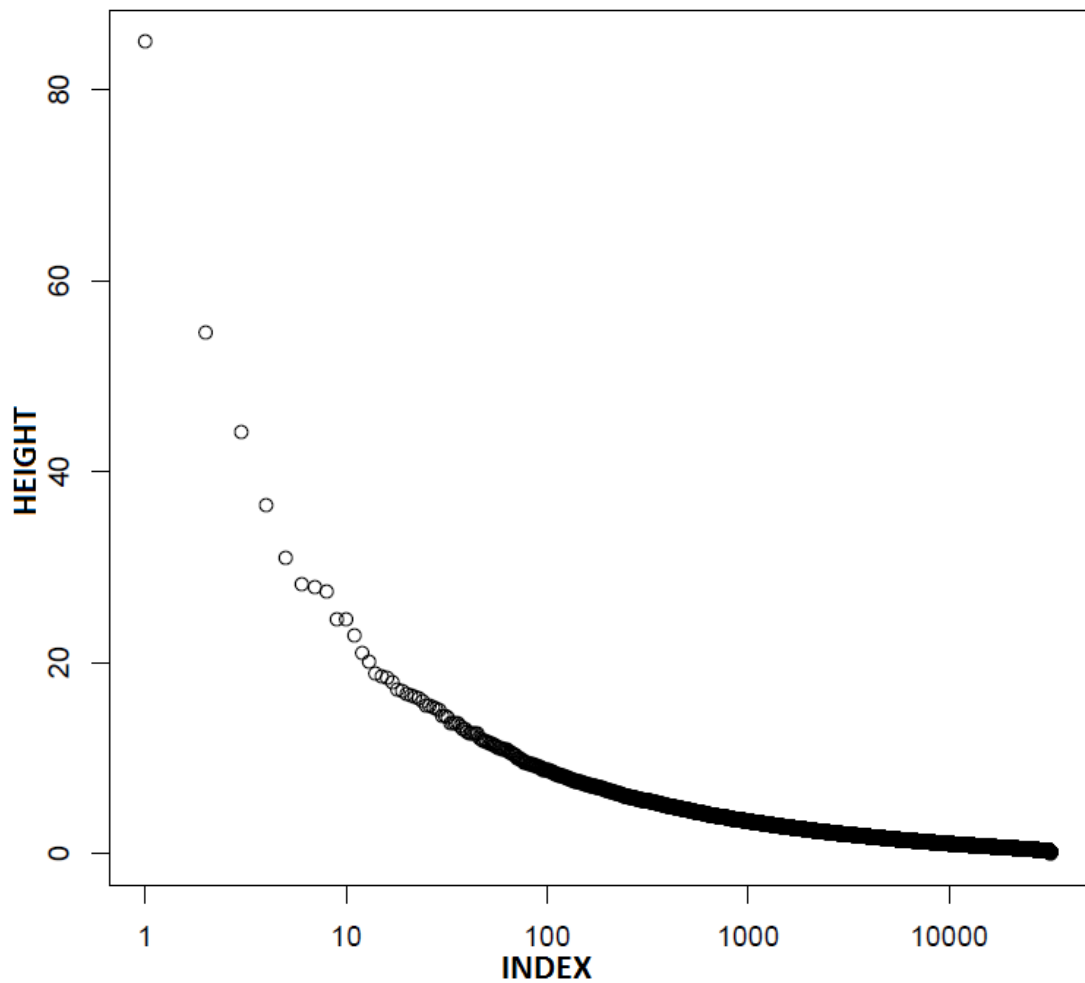


Figure 5-13: Heights plot of the hierarchical clustering excluding the outliers of the urban form dataset. Every branch split is shown with their corresponding height value.

5.2.2.2 K-means clustering

K-means clustering is one of the techniques of partitional cluster analysis and the most common used. Although k-means clustering makes it necessary to define the number of clustering beforehand, its simplicity and intuitiveness procedure provides a beneficial tool to recognize land use typologies based on a diversified dataset of urban form variables. In this research, the definition of the number of clusters considered the outcomes of the hierarchical clustering, a general approach used in previous research (Steinbach et al. 2000*b*) that reinforces the reliability and consistency of the final results of the cluster analysis.

K-means clustering was obtained for the dataset excluding the two outlier groups (834

LSOAs) and tested for both 7 and 8 clusters. Figure 5-14 shows the cluster proportions for each option (adding the two outlier clusters) to provide information about the distribution of the LSOA units found by the cluster analysis. For the first option, two small groups (clusters 2 and 7) and a bigger one (cluster 4) are observed. In contrast, for the 10 clusters option, the bigger group (cluster 5) has a significantly lower percentage than for the previous option (about less 12%) and only one small group (cluster 3) is identified. However, even if this last option reveals a more equally balanced distribution of the set of values, this shouldn't be used alone as validation procedure of the k-means clustering (and cluster analysis overall), as the distribution of values may not match or agree with reality.

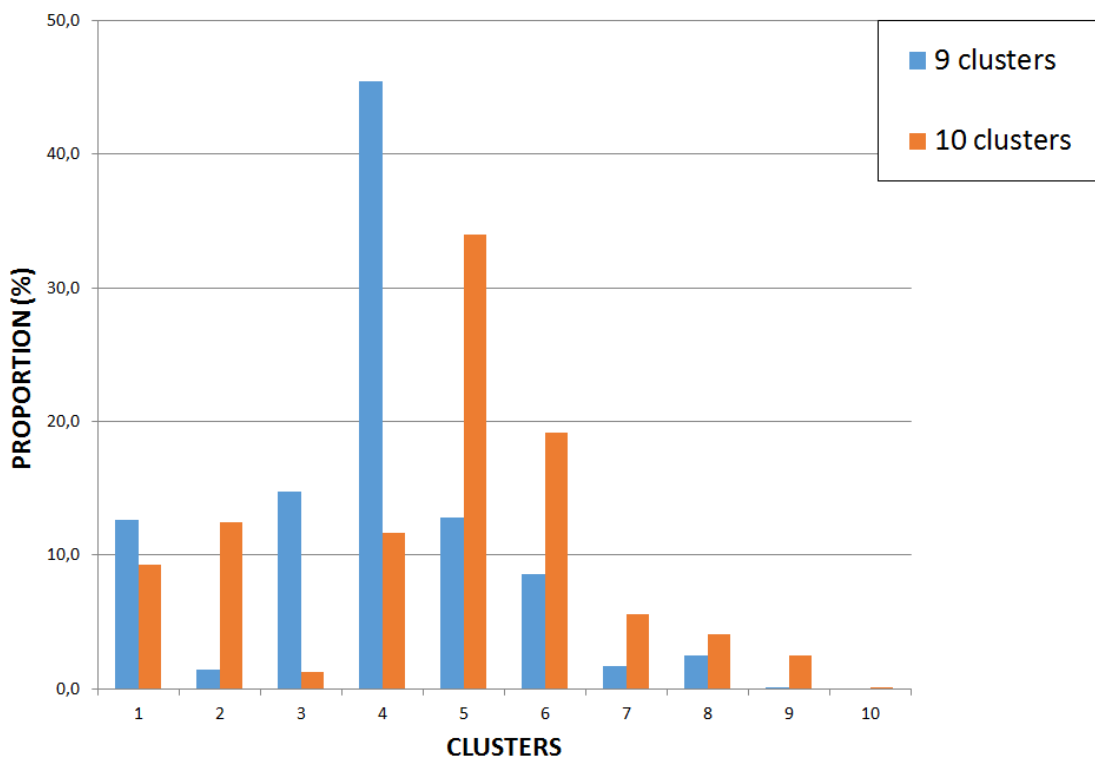


Figure 5-14: Proportions for 9 and 10 clusters resulting from the application of cluster analysis. The last two clusters of each option refer to the outlier sets found in the hierarchical clustering.

Another method to evaluate the results of k-means clustering and validate the consistency of the obtained clusters is calculating the average silhouette coefficients for all clusters. Silhouette coefficients reveal the similarity of each object within its own cluster compared with the remaining clusters, ranging between 1 (well-clustered objects) and -1 (poorly clustered) (Rousseeuw 1987, Brock et al. 2008). This means that the degree of cohesion and separation of every object of a dataset is determined to demonstrate the uniformity

and degree of confidence of the clusters obtained by k-means. Though other methods are available to measure cluster validity, as the Davies-Bouldin index (Davies & Bouldin 1979) and the Dunn index (Dunn 1974), the silhouette width method is more common to k-means clustering, requires a less complex procedure and delivers a graphical output of straightforward interpretation.

In this research, silhouette coefficients were obtained by considering the same object distance used in the k-means clustering procedure – squared Euclidean distance – thus maintaining consistency. As an example, a graphical output was produced not only for the k-means options of 7 and 8 clusters, but also for 2 to 18 clusters (Figure 5-15). Although the best silhouette value (0.60) is for 2 clusters, this number of clusters has no equivalence with the findings from hierarchical clustering and so do not properly represent the analysed dataset. Figure 5-15 also indicates that the coefficients for 7 and 8 clusters are very similar – 0.20 and 0.21 – making both a good choice to illustrate the set of values. Even if these values are not close to 1, for real world data an average silhouette coefficient of more than 0.2 is considered a good result.

In addition to the overall silhouette coefficients of the different total number of clusters, it is also important to assess the within cohesion of each cluster of the two k-means options for total number of clusters. Figure 5-16 shows the similarity within each cluster. Overall, both 7 and 8 clusters have similar cohesion within each cluster membership: only a few clusters reveal coefficient values smaller than zero and so not very uniform.

Following the analysis of Figures 5-14, 5-15 & 5-16, the k-means options of 7 and 8 number of clusters were regarded as valid choice to characterize the dataset resulting of the hierarchical clustering at height=65. Both options reveal reasonable silhouette coefficients and a well-balanced, sensible distribution of the set of values. Figures 5-17 & 5-18 map both alternatives (and adding the two identified outlier clusters) to represent the land use of England. The maps reveal similarities, showing the more densely populated areas (see Figure 5-8 on page 85) located mainly in the same clusters 1, 2 and 3, estimated as the major urban areas. This means that the cluster representation results in an expected description of the urban system in England composed by: (i) main city centres; (ii) surrounding high and low density urban areas; (iii) transition peri-urban/rural areas; and (iv) essentially rural and agricultural areas.

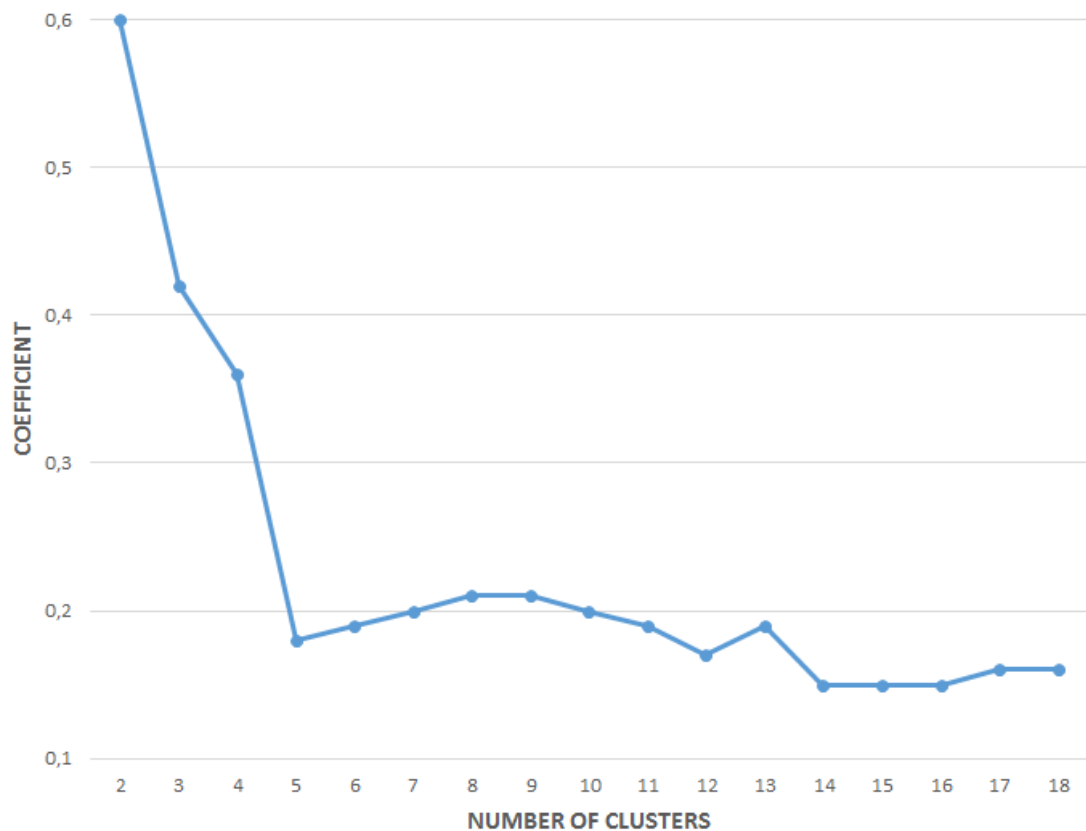


Figure 5-15: Silhouette coefficients for 2 to 18 clusters of the k-means clustering for the urban form dataset (excluding the outliers set).

5.2.3 Focusing on the land use clusters

Considering that both options – 9 and 10 clusters – are suggested as valid to characterize the land use in England, additional analysis was performed. This analysis was focused on the information provided by both alternatives about the transition areas. Therefore, an example area was analysed: Figure 5-19 shows that the areas *A* and *B* include areas with buildings, which should be considered mainly urbanized. However, the 10 clusters option (b) includes them in a transition-like land use typology, similar to areas located West of *A*, where fields are easily recognized. Consequently, the 9 cluster option (a) was considered to characterize better the land use typology in England for the simplicity purpose of this research. The analysis of the relationship between urban form and energy consumption (see section 5.3) employs 9 clusters.

Taking into account Figure 5-17 as representing the land use in England, Table 5.2 proposes the denomination of the respective clusters. Their respective proportions (as seen in Figure

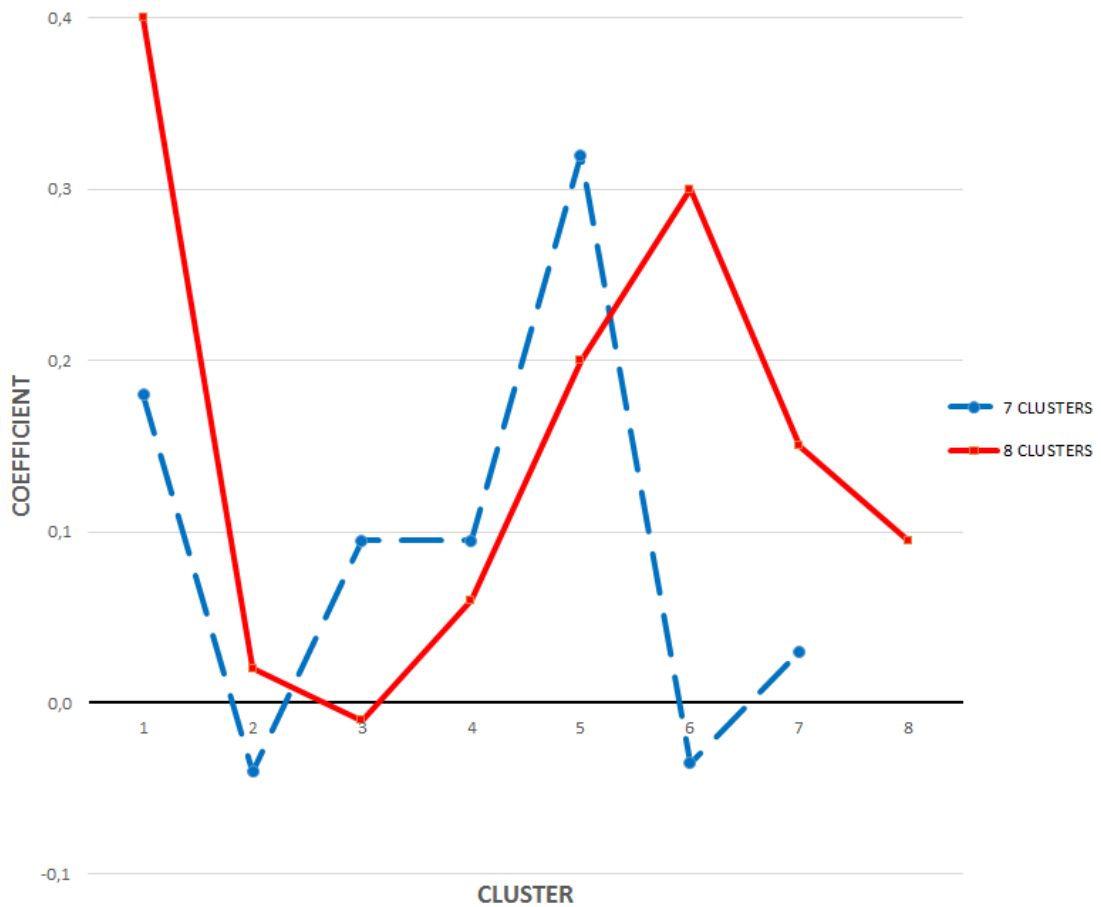


Figure 5-16: Silhouette coefficients for each cluster of the k-means clustering for the urban form dataset (excluding the outliers set), considering 7 and 8 clusters.

5-14) are also shown in the Table 5.2. The naming of the clusters follows standard labelling as found, for example, in the Corine Land Cover (EEA 2017), though simplified and adapted to the total number of clusters identified in the analysis.

Table 5.2: Land use typologies (including abbreviations) and respective proportions of LSOA units and surface area based on the cluster analysis.

CLUSTER	LAND USE TYPOLOGY	LSOA PROPORTIONS (%)	SURFACE AREA PROPORTIONS (%)
1	City centre areas (<i>city</i>)	12.68	0.52
2	Other city centre areas (<i>city other</i>)	1.41	0.04
3	Urban areas: high density (<i>high dens</i>)	14.77	5.11
4	Urban areas: low density (<i>low dens</i>)	45.46	9.54
5	Other urban areas (<i>other urban</i>)	12.83	3.92
6	Peri-urban/transition areas (<i>peri-urban</i>)	8.58	39.21
7	Rural or unused areas (<i>rural</i>)	1.73	30.95
8	Mainly rural areas (<i>other rural</i>)	2.52	9.45
9	Forest lands (<i>forest</i>)	0.02	1.27

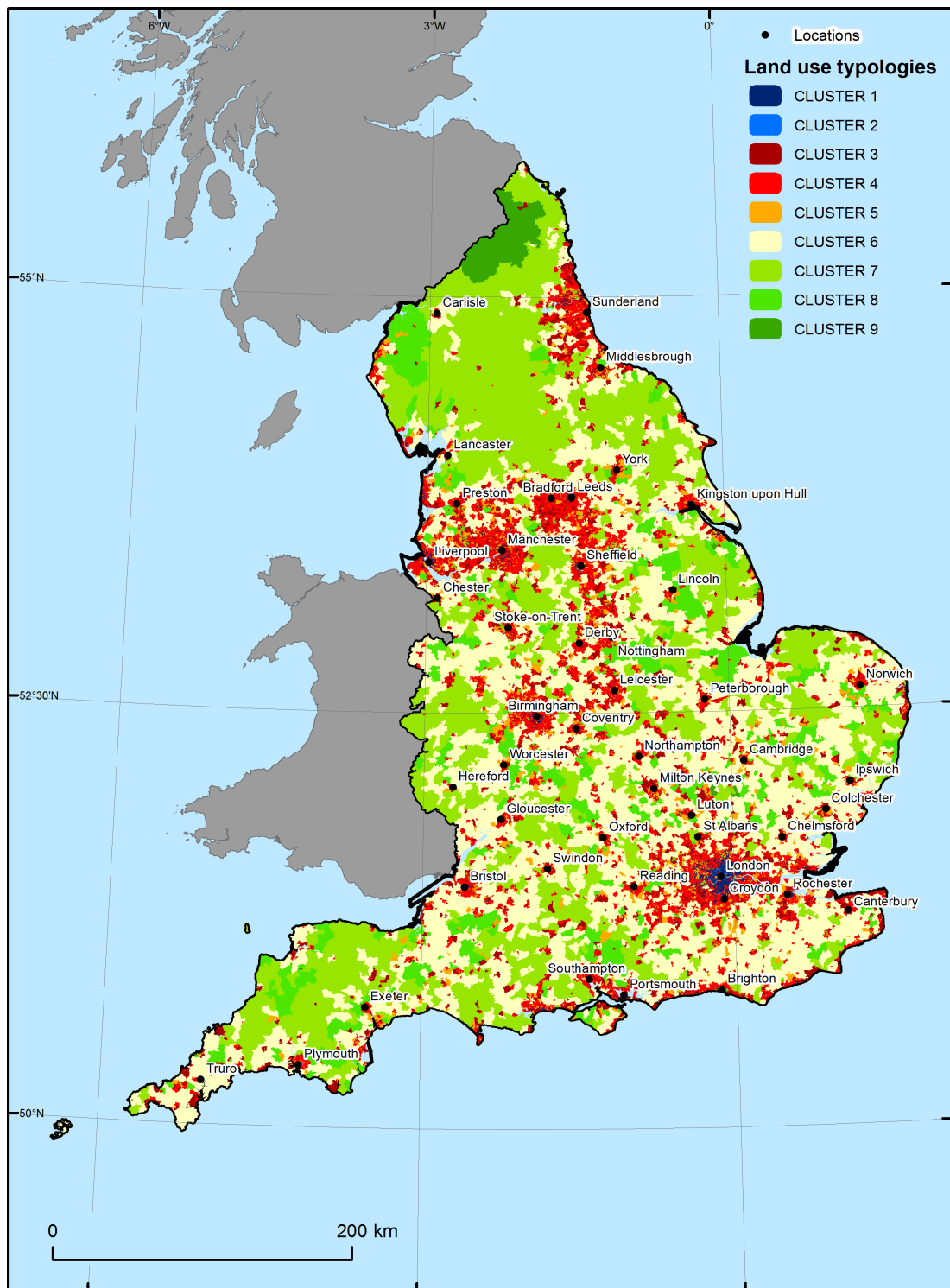


Figure 5-17: Land use typologies with 9 clusters by LSOA in England. Based on: ONS (raw cartography) – Contains National Statistics data ©Crown copyright and database right [2011].

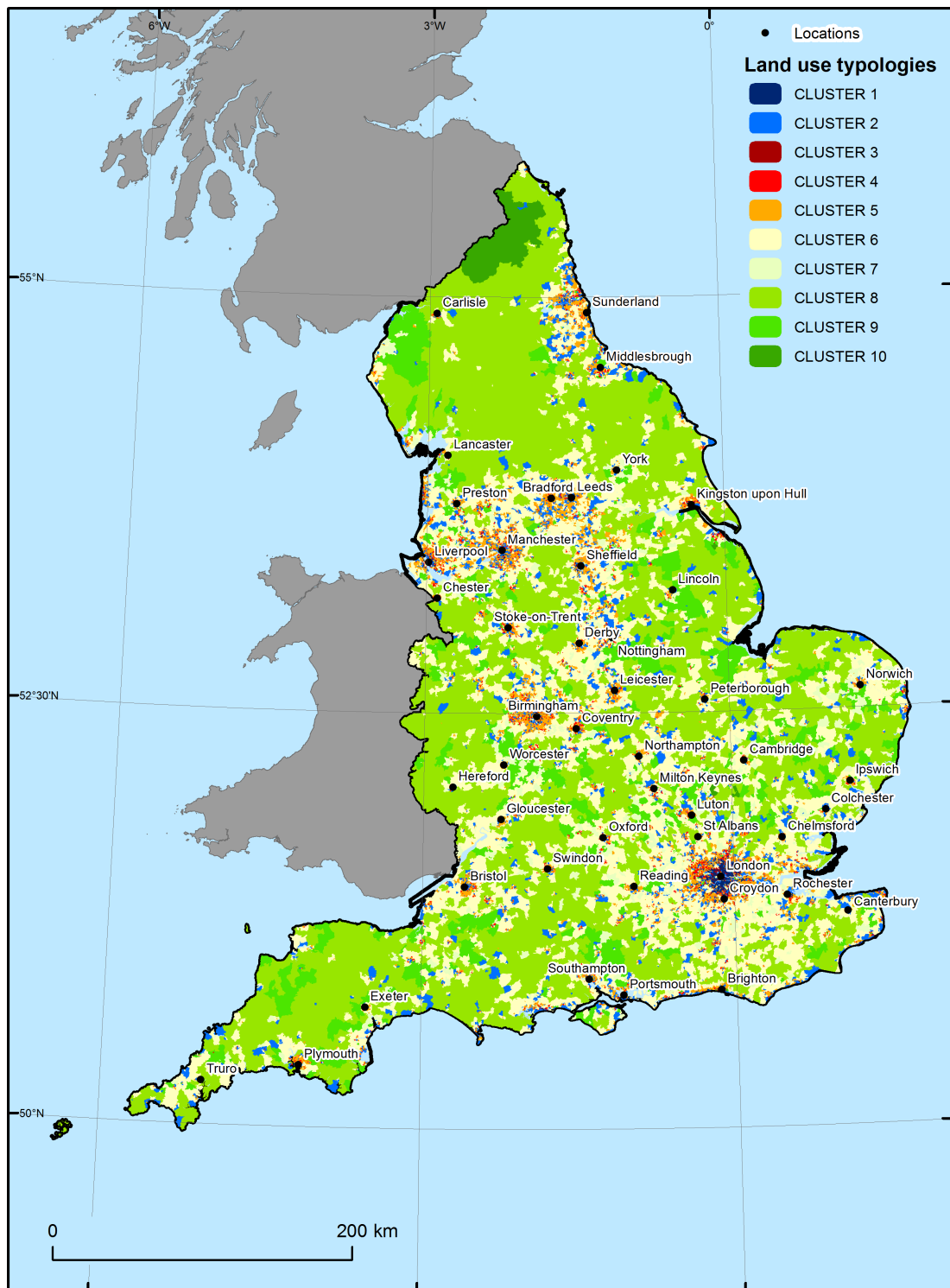


Figure 5-18: Land use typologies with 10 clusters by LSOA in England. Based on: ONS (raw cartography) – Contains National Statistics data ©Crown copyright and database right [2011].



Figure 5-19: Land use typologies with 9 clusters (a) and 10 clusters (b) by LSOA in Hereford. Colours: red, orange and blue – urbanized areas; yellow – transition-like areas; green – rural areas. Based on: ONS, ESRI, GeoEye, and others (raw cartography, raw land cover) – Contains National Statistics data ©Crown copyright and database right [2011].

The land use classification is an important tool of land description and management. However, standard land use classification systems using terms as “residential use” or “consolidated urban area” do not show land use in terms of function, mix-use and changes over time (Chen 2014, Nel et al. 2017). Some research suggests that these changes in urban land use and their extension may have even been underestimated when employing, for example, aerial photography or alike methodologies to calculate them (Nel et al. 2017). Additionally, much of the land use classifications are not associated with fields as transport and energy consumption (Chen 2014). This leads problems to policymakers that seek to understand the overall process of a region and propose long-term planning strategies. In this work, land use typologies (based on a cluster analysis) are suggested to understand and quantify their relationship with energy consumption at LSOA resolution.

As observed in the map (Figure 5-17), the majority of LSOA units referring to rural or unused areas are located in the North and Cornwall. Although representing less than 1.8% of all LSOAs (*Cluster 7*), these areas cover about 31% of all surface area of England. On the other hand, the transition areas represent about 8.5% of all LSOA units (*Cluster 6*), but include almost 40% of the surface area of England. These are the areas that may be undergoing an urbanization process due to the expansion of residential or commercial areas. The highest proportion of LSOAs refers to Cluster 4 (urban areas: residential) with almost 45.5%, though only covering about 9.5% of the surface area. The significant proportion of this Cluster 4 reveals the high degree of urbanization in England, although much of these areas are not totally covered by building-like urbanization, but include mix land use generally included in the urban process.

5.3 Relationship between energy and urban form

Cities and urban areas are complex systems that concentrate population, economic and cultural activities, governments and other (Hillier & Vaughan 2007, Barthelémy et al. 2013, Batty & Marshall 2012, Fujita et al. 1999, UN-DESA 2014). Many theories and research have tried to understand those complex systems and related dynamics taking shape in every country and region (Portugali et al. 2012, Jiang et al. 2012, Samet 2013), but no final solution has been found. In this thesis, the approach focused only on the energy consumption aspect of the urban systems to understand the relationship between that operational energy and urban form variables. This is expected to provide valuable information to planners and policymakers about the dynamics and the influence of these variables on energy to support the design and redesign of novel strategies that, overall, endeavour to reduce and mitigate the carbon-related energy consumption. As mentioned before, the analysis of

that relationship is based on two methods: scaling laws dependencies and correlation. The results and discussion of those analyses follows. In section 5.3.1, the scaling dependencies are studied for the whole LSOA dataset, cities and land use clusters to show the different relationships that urban variables and energy consumption between themselves. This is followed by section 5.3.2 that analyses the correlations established between the two datasets and it is structured similarly to the previous section: review of the correlations by LSOA, cities and land use clusters.

5.3.1 Scaling laws dependencies and consequences

The scaling laws relationships have been applied to understand the variance of different socio-economic characteristics in relation to population size (Gomez-Lievano et al. 2012, Schlöpfer et al. 2014). In this research, scaling is applied to energy consumption at LSOA level to examine its relationship with different urban form variables (listed in Table 5.3), expanding the use of that methodological approach to study the dynamics and complexity of cities and general urban areas. The presented results are shown on a dual-log scale so that a power-law scaling appears as a linear relationship (Eqn. 4.9). This allows simple linear regression techniques to be used to both fit the exponent and obtain correlation strengths. In section 5.3.1.1 the scaling trends for the whole LSOA dataset is analysed, followed by the discussion for selected cities (section 5.3.1.2) and land use clusters (section 5.3.1.4).

5.3.1.1 Scaling trends for the LSOA units

The analysis of scaling dependencies shows a prevalence of an economy of scale of energy consumption regarding the majority of the urban variables, i.e. energy demonstrates a sublinear scaling behaviour. This behaviour is observed for the total energy (Figure 5-20), and both the energy consumption of buildings and commute transport (Figures 5-21 and 5-22). The sublinear scaling demonstrates that an increase in the values of those urban variables will have a smaller effect on energy consumption.

Figure 5-20 also reveals that energy consumption does not comply with a linear scaling and even has negative values for a significant number (about 28%) of the urban form variables or indicators. Many density (population, dwellings, household spaces) and proportion variables (built-up area, area of buildings, etc.) are included in this latter scaling group. Therefore, these variables reveal an inverse scaling relationship with energy consumption by LSOA level, expressing a negative impact on consumption with their increase, thus favouring the

Table 5.3: Key for the urban form variables (and abbreviations) used in the scaling and correlation plots, as Figure 5-20.

ID	URBAN FORM VARIABLE
1	Perimeter of the geographical unit (<i>perimeter</i>)
2	Surface area (<i>area</i>)
3	Area of domestic buildings (<i>dom buildings</i>)
4	Area of road network (<i>road</i>)
5	Road length (<i>road len</i>)
6	Density of road length (<i>road dens</i>)
7	Area of railway (<i>rail</i>)
8	Extent of built-up area (<i>built-up</i>)
9	Proportion of built-up area (<i>built-up prop</i>)
10	Area of buildings (<i>buildings</i>)
11	Proportion of area of buildings (<i>buildings prop</i>)
12	Extent of non-built-up area (<i>non-built-up</i>)
13	Ratio of open space (<i>open space</i>)
14	Proportion of detached dwellings (<i>detached</i>)
15	Proportion of semi-detached dwellings (<i>semi-detached</i>)
16	Green space (<i>green</i>)
17	Resident population (<i>pop</i>)
18	Male resident population ratio (<i>male pop</i>)
19	Population density (<i>dens pop</i>)
20	Population density in built-up area (<i>dens pop built-up</i>)
21	Number of dwellings (<i>dwel</i>)
22	Dwellings density (<i>dwel dens</i>)
23	Number of household spaces (<i>households</i>)
24	Density of household spaces (<i>households dens</i>)
25	Density of household spaces in built-up area (<i>hh dens built-up</i>)
26	Private car availability per 1000 inhabitants (<i>car</i>)
27	Proportion of population with higher education (<i>high educ</i>)
28	Proportion of population in employment (<i>employment</i>)
29	Proportion of population employed in services (<i>employ services</i>)
30	Proportion of flats in commercial building (<i>flat commer</i>)
31	Ratio of detached houses per flat (<i>detached flat</i>)
32	Yearly household income (<i>income</i>)

compact city theory that refers to the better energy efficiency of more densely populated cities and urban areas. Further analysis of Figure 5-20 shows that superlinear scaling is also unrepresented, i.e. energy consumption does not follow the opposite of economies of scale in relation to the considered urban form variables.

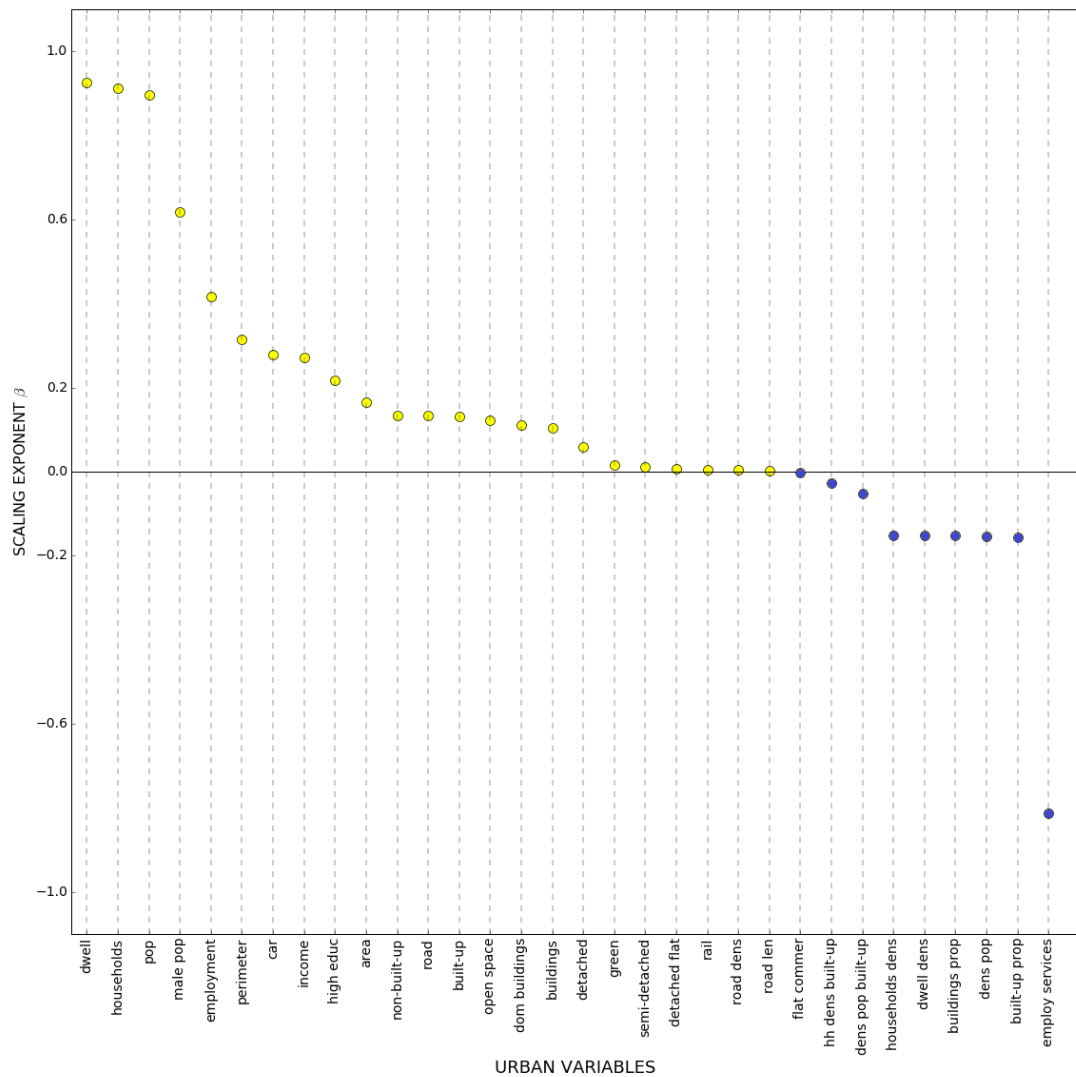


Figure 5-20: Power-law exponents by urban form variable for the total energy consumption by LSOA in England, arranged by value. Blue circles: non-linear scaling; Yellow circles: sublinear scaling – Table 5.3 for the key to urban form variables.

5.3.1.2 Scaling for LA units

Similarly to what is observed for the whole LSOA units set, Figure 5-23 shows that for the majority of the 12 randomly selected Local Authorities (LAs)¹ in England, total energy consumption complies with sublinear in relation with the urban form variables, i.e. scaling exponent values are between 0 and 1. However, total energy consumption also shows scaling relationships with negative β values for a significant number of urban variables, in the same way as found for all LSOAs (Figure 5-20). Yet, differences are observed among

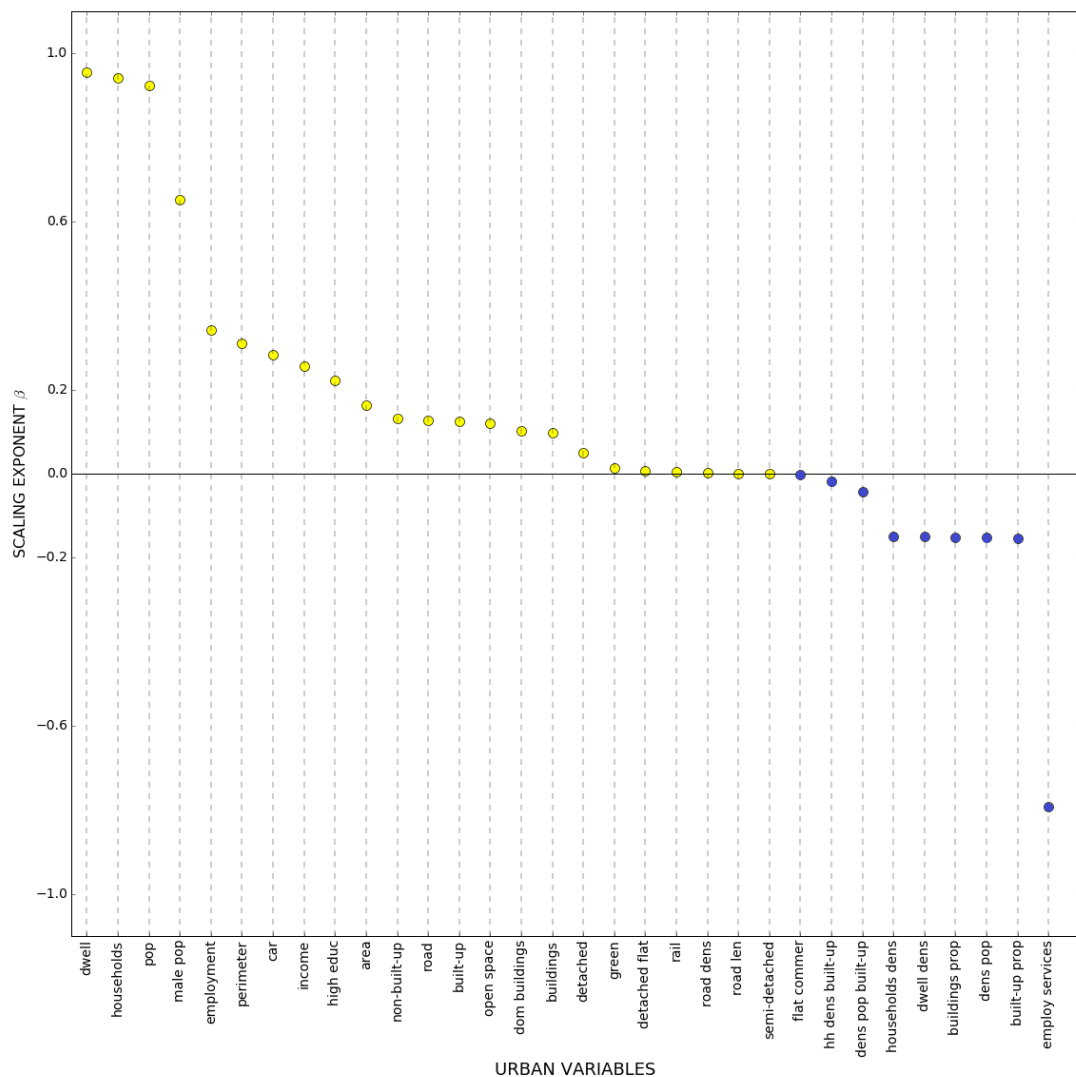


Figure 5-21: Power-law exponents by urban form variable for the energy consumption of buildings by LSOA in England, arranged by value. Blue circles: non-linear scaling; Yellow circles: sublinear scaling – Key to urban form variables found in Table 5.3.

cities.

Local Authorities located within the Greater London region – Croydon and Westminster – show a bigger number of urban variables with linear or superlinear scaling behaviour than the remaining. The City of Westminster is particularly relevant as one of the variables showing superlinear scaling exponent is the proportion of population employed in services

¹Local Authorities shouldn't be considered cities though some cover the actual territory of the cities, such as Bristol and Manchester.

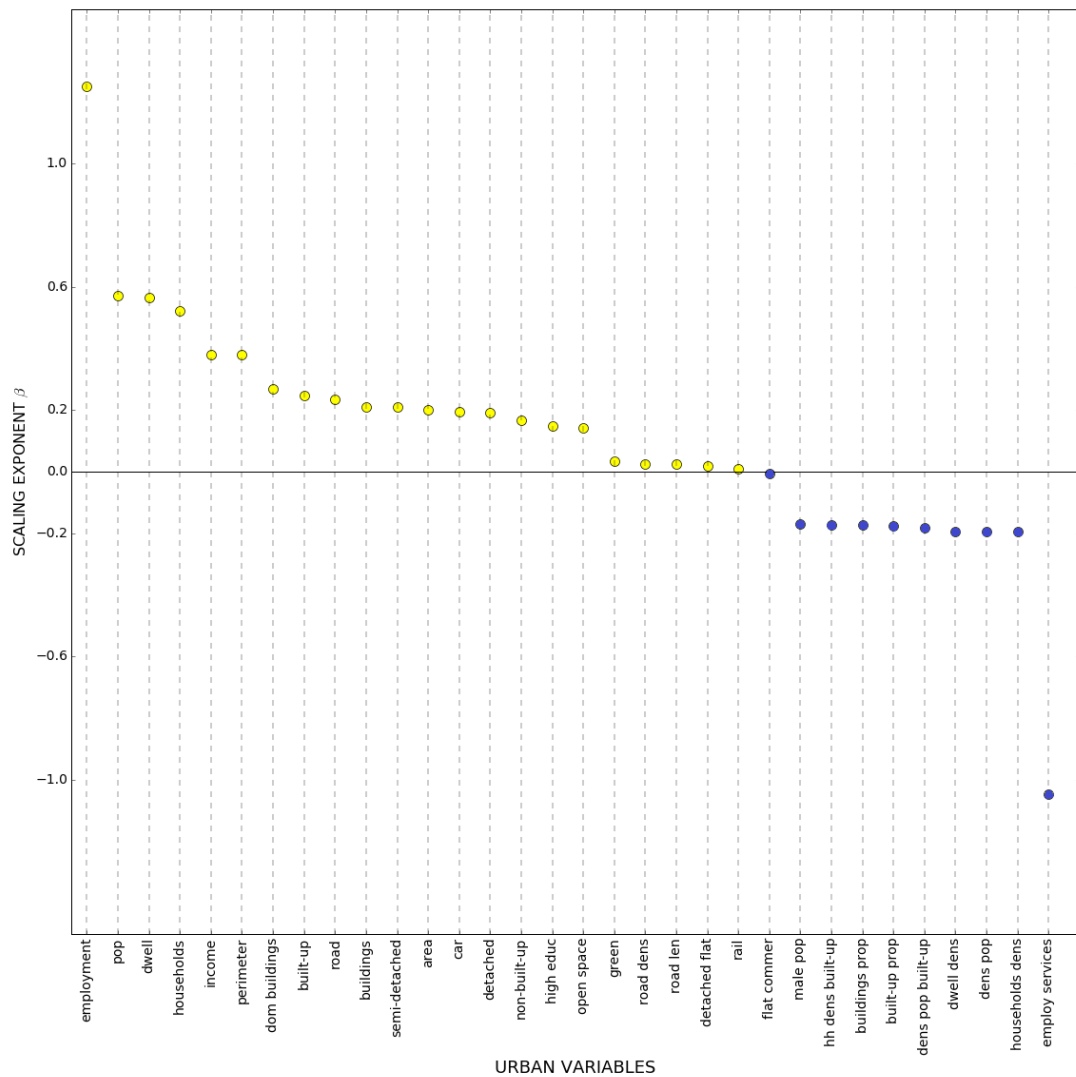


Figure 5-22: Power-law exponents by urban form variable for the energy consumption of commute transport by LSOA in England, arranged by value. Blue circles: non-linear scaling; Yellow circles: sublinear scaling – Key to urban form variables found in Table 5.3.

(variable 29). This reveals that the increase of that workforce has a significant impact on the growth of energy consumption, providing new and significant information about energy use.

The analysis of Figure 5-23 does not seem to reveal a trend between locations, i.e. both big and smaller LAs show a prevalence of sublinear scaling of energy consumption to much of the urban variables (above 60% of the variables in average). However, similarities are found between Milton Keynes and Plymouth. These LAs with comparable population, but

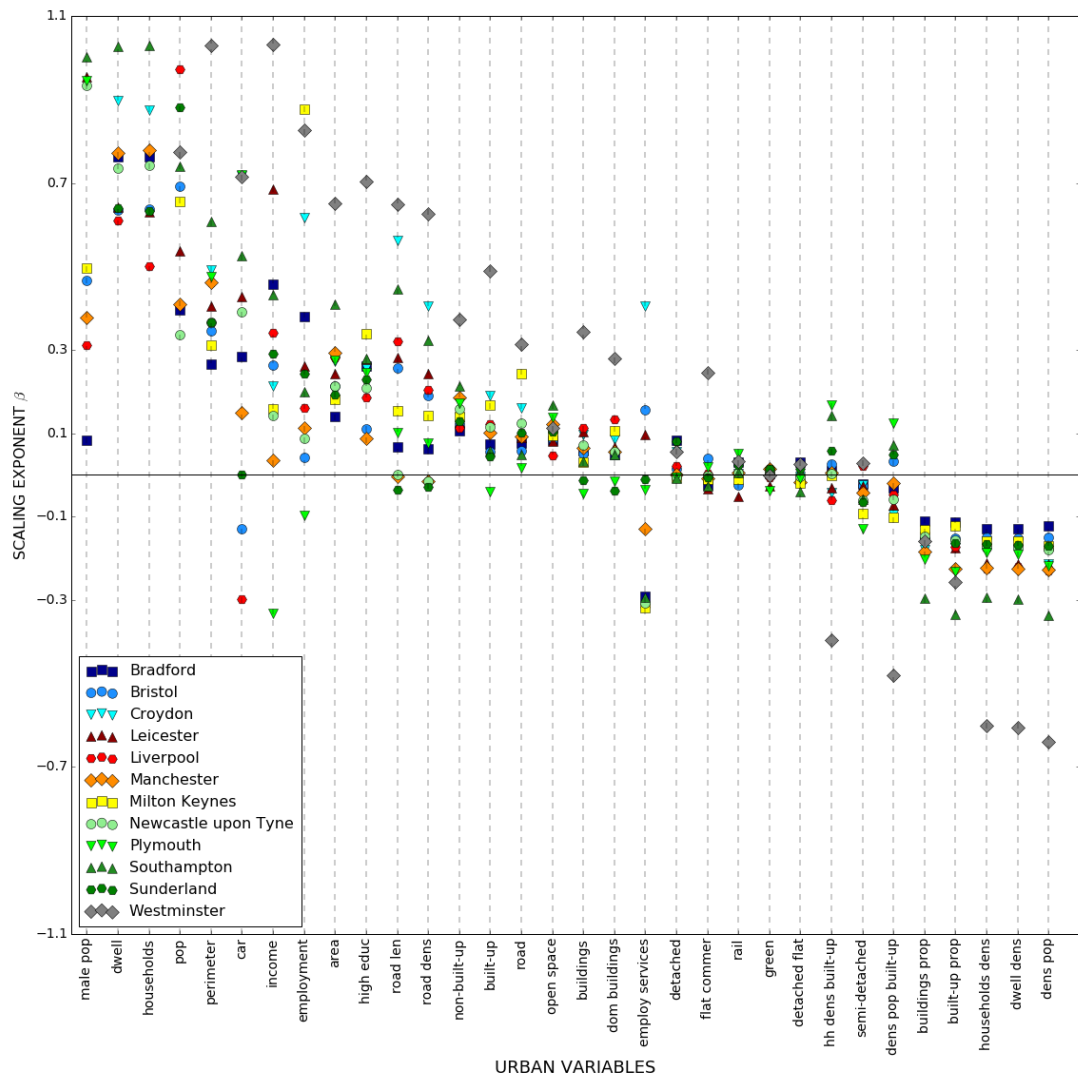


Figure 5-23: Power-law exponents by urban form variable for the total energy consumption of selected LAs in England, arranged by value. Exponents higher than 1.1 are not shown – Table 5.3 for the key to urban form variables.

different historical background, present the same proportion of urban variables with which energy consumption has superlinear scaling. Although one of the variables is different, this also reveals new insights about the structure of the LAs. If for Milton Keynes that variable refers to car availability, for Plymouth that contrasting variable is population. This may show that new LAs are more car dependent and historical LAs are more population-dependent (see section 6.3.1 for further discussion).

5.3.1.3 Example of the scaling for LAs

In addition to the differences between LAs, there are different scaling values for the various urban form variables. Looking into Figure 5-24, it is possible to notice a variation among LAs regarding the relationship between total energy consumption and variable 29, the proportion of population employed in services. The figure reveals that this variable has a strong superlinear scaling effect on energy consumption for the City of Westminster, demonstrating a big difference with the remaining LAs. Further analysis shows the existence of three other groups by scaling exponent value: (i) inverse scaling relationship that includes, mostly, LAs located in the North of England, as Liverpool and Newcastle upon Tyne, (ii) not significant scaling, covering mainly LAs in the South of England, as Bristol and Plymouth; and (iii) sublinear scaling for Croydon only. However, considering the error of the scaling exponents for variable 29, some LAs can be included in two types of scaling (except the City of Westminster, clearly distinct from the remaining), although three types of scaling behaviour are observed. This means that though a variation of scaling values is noticed, that variation is not enough to distinguish LAs, not only for variable 29 but also others such as variables 26 and 32.

5.3.1.4 Scaling for land use clusters

Moving from the analysis of scaling behaviours for LAs, Figure 5-25 reveals the difference of scaling values between energy and the various urban variables for the obtained land use clusters. The difference between LAs and land use clusters is also observed by the order of the urban variables on the x axis. Figure 5-25 shows a prevalence of sublinear scaling exponent values for all clusters, as well as a significant inverse scaling relationships, similarly of what is found for LAs (Figure 5-23). Nevertheless, it is possible to observe dissimilarities. Cluster 9 is a noticeable case since it presents a higher proportion of inverse scaling (more than 55% of the urban variables). This is not surprising given the “outlier” characteristic of this cluster, which includes only 6 LSOA units. In fact, for both “outlier” clusters (8 and 9), energy consumption shows bigger proportion of inverse relationships with the considered urban form variables.

Clusters 3 and 4 show more urban form variables with sublinear scaling exponents than the remaining clusters (Figure 5-25). These clusters correspond essentially to transition areas between high and low density urban areas (suburbs), demonstrated, for example, by the superlinear scaling of the number of dwellings and household spaces (variables 21 and 23) for Cluster 3. The increase in value of those urban variables still has a considerable impact

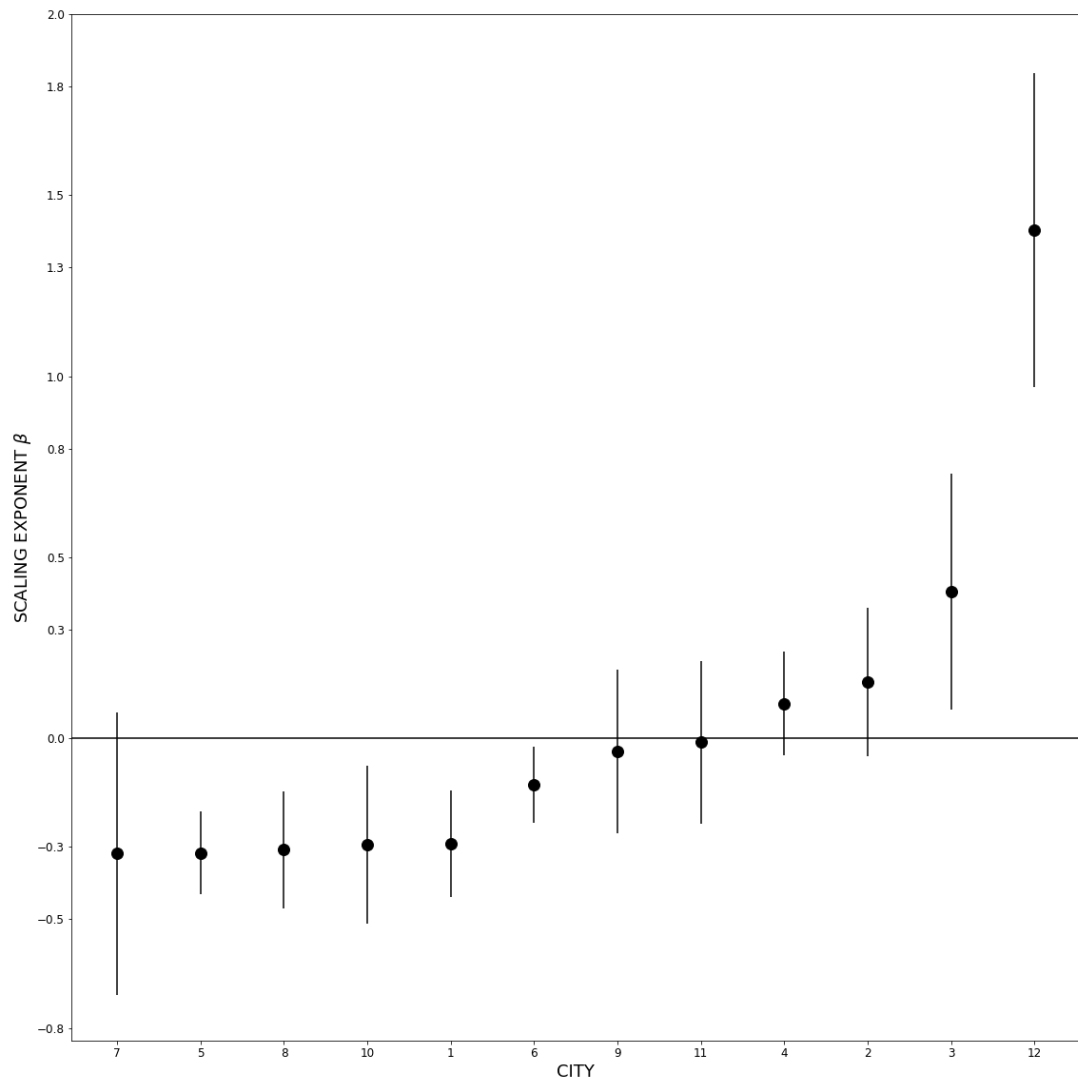


Figure 5-24: Power-law exponents and respective error for the relationship between the total energy consumption and urban variable 29 for selected LAs in England: (1) Bradford, (2) Bristol, (3) Croydon, (4) Leicester, (5) Liverpool, (6) Manchester, (7) Milton Keynes, (8) Newcastle upon Tyne, (9) Plymouth, (10) Southampton, (11) Sunderland, (12) Westminster.

on the rise of energy consumption.

The overall sublinear scaling behaviour observed, essentially, for Clusters 1-3 shows an economy of scale. This means that the increases on the different urban variables have lower impact on the decrease of energy consumption, and will only lead to the compact city-related negative consequences. Therefore, reducing consumption with the expansion of, for example, population density is counterproductive for already densely populated areas

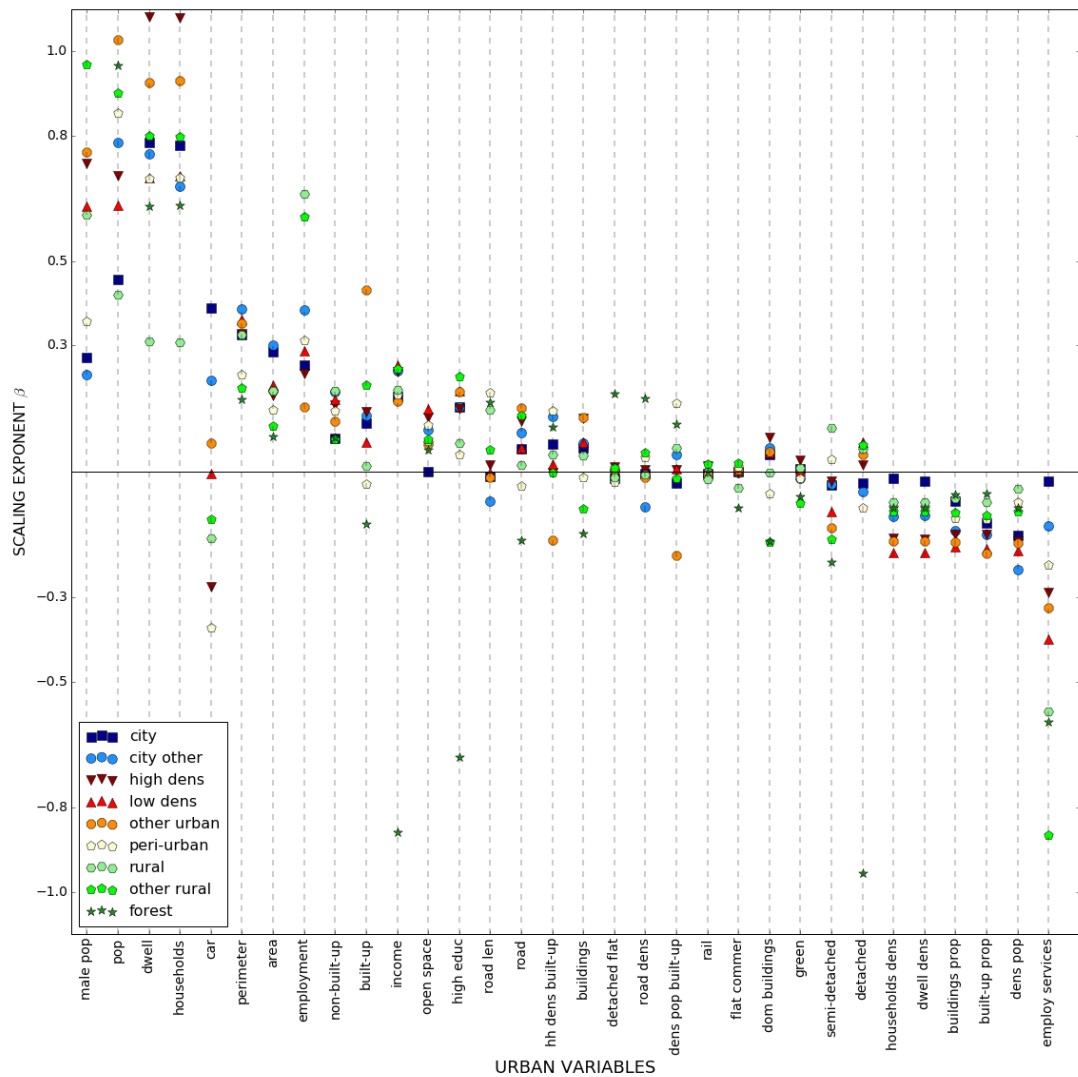


Figure 5-25: Power-law exponents by urban form variable for the total energy consumption by land use clusters in England and at LSOA level, arranged by value. Exponents higher than 1.1 and lower than -1.1 are not shown – Key to urban form variables found in Table 5.3.

such as these Clusters 1-3. The actual effects of the increase of population density on consumption are most likely to be observed in suburbs or (yet) low density areas represented by Clusters 4-6.

Figure 5-25 also reveals that socio-economic indicators produce bigger effects on energy consumption than landscape metrics. As observed, much of the socio-economic variables show scaling exponents above 0.5 – for example population (variable 17), male population

(18), number of dwellings (21) and number of household spaces (23) – for a large number of clusters. The physical urban variables, such as the road length (variable 5), proportion of built-up area (8) and proportion of area of buildings (11), demonstrate a prevalence of inverse or sublinear scaling relationships. This brings new information to policymakers and planners about the focus of their actions (see discussion in section 6.3.1).

5.3.1.5 Example of the scaling for land use clusters

The prevalence of sublinear scaling of total energy consumption for the majority of urban form variables by land use cluster does not mean that the behaviour of these clusters is completely similar. As an example, Figure 5-26 shows the variation of scaling exponent values of variable 13 (ratio of open space) by land use cluster. It is observed that the scaling span of Clusters 2, 7 and 9 is bigger than for the remaining. Even if the sublinear scaling is still observed, the impact on energy consumption of the increase or decrease of variable 13 varies greatly for those clusters. This draws attention to the need to examine in more detail the reasons for that variation, in order to outline actions that produce the same mitigation effect on energy as on the remaining clusters.

5.3.1.6 Summary

The analysis of scaling laws relationships shows some relevant results such as the prevalent sublinear scaling, revealing the main urban form variables influencing energy consumption, as well as differences between LSOAs, LAs and land use clusters. Making a summary of the analysis, it is possible to declare that there is:

1. prevalent sublinear behaviour of most of the urban variables in relation to energy;
2. significant number of variables showing inverse scaling relationships;
3. essentially an economy of scale by energy consumption;
4. bigger impact of socio-economic variables on energy consumption than physical variables;
5. larger number of variables with linear and superlinear scaling regimes for LAs located in the Greater London region;
6. important impact of the proportion of population employed in services (variable 29) on the energy consumption in the City of Westminster;

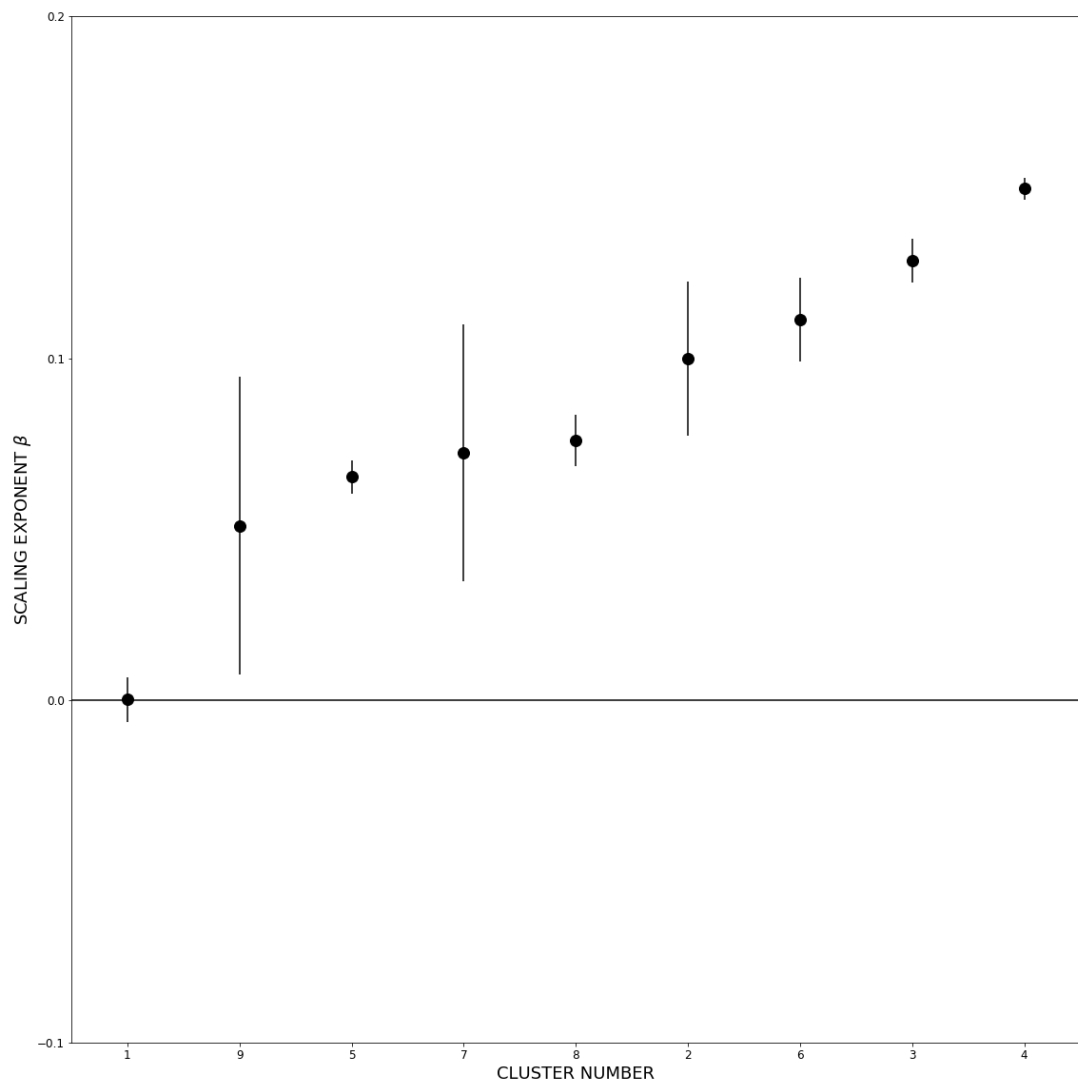


Figure 5-26: Power-law exponents and respective error for the relationship between the total energy consumption and urban variable *13* for the (9) land use clusters in England at LSOA level.

7. more car dependency of new LAs (e.g. Milton Keynes) due to superlinear scaling of car availability (variable 26);
8. prevalence of inverse scaling relationships of “outlier” land use clusters (Clusters 8 and 9);
9. different scaling behaviour of essentially urban and transition/rural land use clusters.

5.3.2 Correlation

Since the seminal work of the seminal work by Newman and Kenworthy (Newman & Kenworthy 1989), correlation studies to understand the relationship between energy and urban variables have been prolific. However, most focus on transport energy, as for example the Land Use and Transportation models (Kitchen et al. 2011, Troy et al. 2012, Rode et al. 2014). As mentioned, in this research the understanding of that relationship is based on correlation and scaling values, covering the total energy consumption by LSOA level, as well as the individual consumption of buildings and commute transport. In section 5.3.2.1 the overall correlation trends are discussed, including a brief analysis by buildings and transport energy consumption alone, by region and for two LAs (section 5.3.2.2). This is followed by the analysis of correlations for all urban variables by LSOA (section 5.3.2.3), selected LAs (section 5.3.2.5) and land use clusters or typologies (section 5.3.2.6), including the analysis by sectors (sections 5.3.2.4 and 5.3.2.7).

5.3.2.1 General correlation trends

Correlation can be graphically observed by the goodness of the fit of the relationship between two variables. Figure 5-27 shows two distinct trends (as observed by eye) for the relationship between total energy consumption and population density: a stronger bottom one, and an additional trend that favours energy efficiency, i.e. increases of density results in lower energy consumption. These trends indicate that the different physical and socio-economic characteristics of the LSOA units have contrasting impacts on energy consumption and efficiency, and thus there is not a regular fit between the variables. One potential hypothesis is that each trend describes energy consumption of buildings and commute transport, respectively.

Figure 5-28, however, reveals that the two trends are still observed for buildings energy consumption (a). Furthermore, the trends observed for the energy consumption of commute transport (Figure 5-28b) are distinct from the ones demonstrated for the total energy consumption. This means that other factors should be influencing energy consumption at LSOA level, suggesting further analysis. Additionally, the observed trends are also noticed for other urban variables, such as perimeter (1) and dwellings density (22), though other variables do not show a tendency (thus, correlation).

The aforementioned trends are also observed when analysing the regions of England (Figure 5-29). The strength of the correlation between total energy consumption and population density varies according to region. The dissimilarities are essentially between the Greater

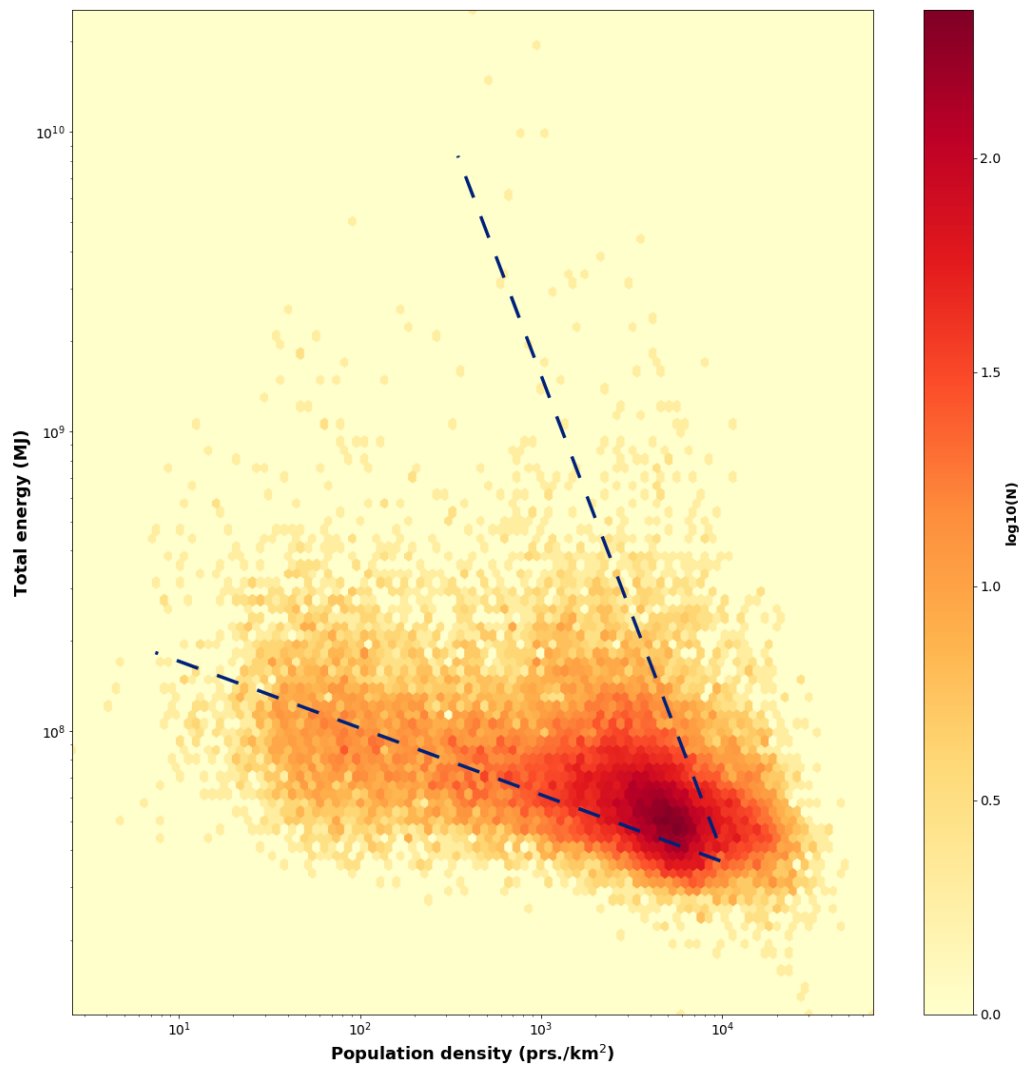


Figure 5-27: Density plot of the relationship between total energy consumption and population density by LSOA level in England. Blue dotted lines: estimated correlation trends (by eye).

London region (pink coloured) and the remaining: although demonstrating more energy consumption, that Greater London shows better energy efficiency regarding population density. Consequently, a small increase of population density in Greater London leads to a significant decrease of total energy consumption. For other regions, that behaviour trend is not observed, thus demonstrating lower energy efficiency. The differences found among regions for population density and other urban variables such as I (perimeter), makes way to the study of energy consumption at more detailed scales.

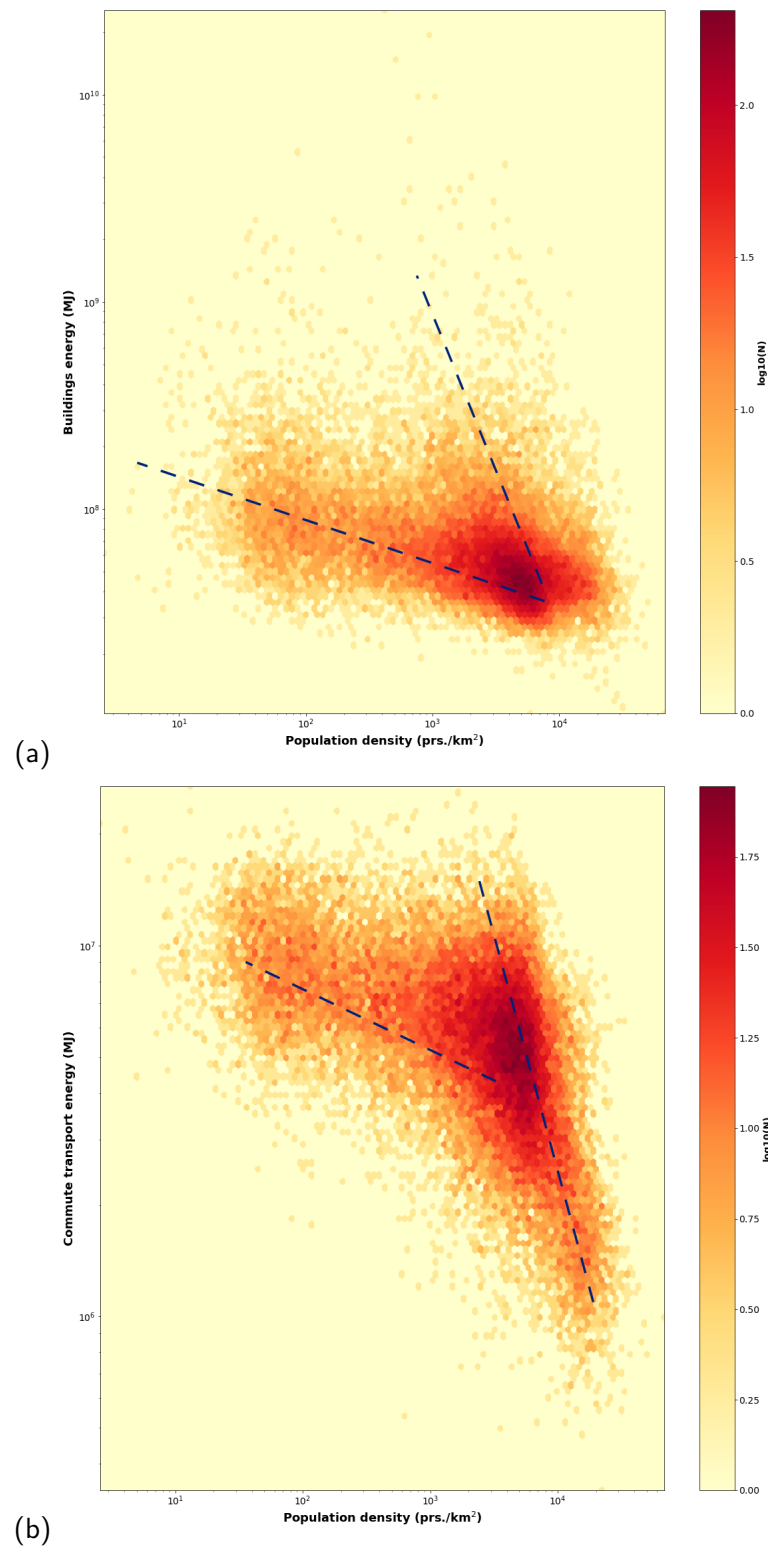


Figure 5-28: Density plots of the relationship between energy consumption of buildings (a) and commute transport (b) and population density by LSOA level in England. Blue dotted lines: estimated correlation trends (by eye).

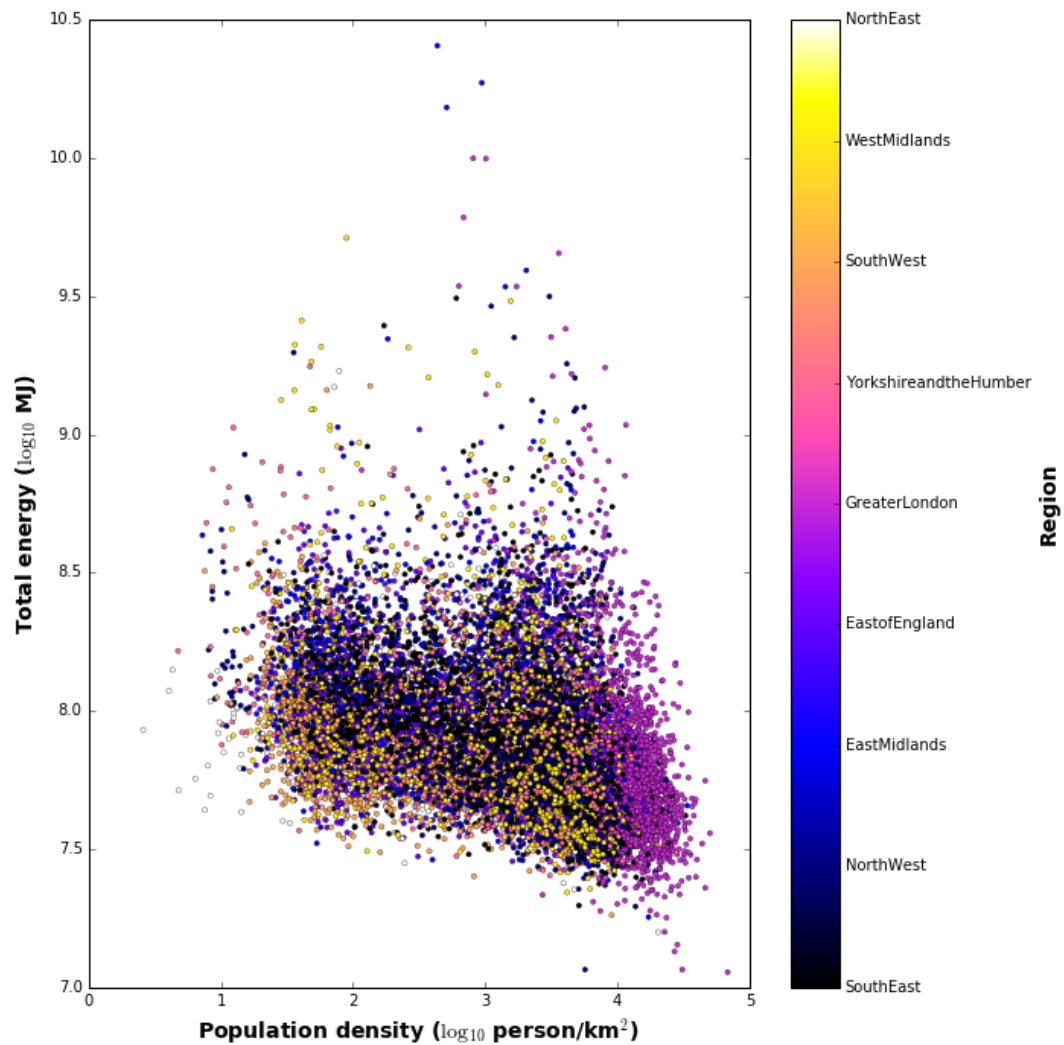


Figure 5-29: Relationship between total energy consumption and population density by LSOA level in England where every dot represents a LSOA unit.

5.3.2.2 Correlation trends at LA scale: an example

A more detailed geographic scale is, for example, LA level. Figures 5-30 and 5-31 describe the relationship between sectorial energy consumption and population density for two Local Authorities (LAs) of England with similar population sizes – Milton Keynes (248,821 inhabitants) and Plymouth (256,384) –, but distinct historical occupation (Milton Keynes was created only in 1974 (Parliament of the United Kingdom 1972)). It is shown that, also at LA scale, the hypothesis of having two different and clear correlation trends for buildings and transport energy is not confirmed. In fact, Figure 5-30a reveals multiple trends (Figure

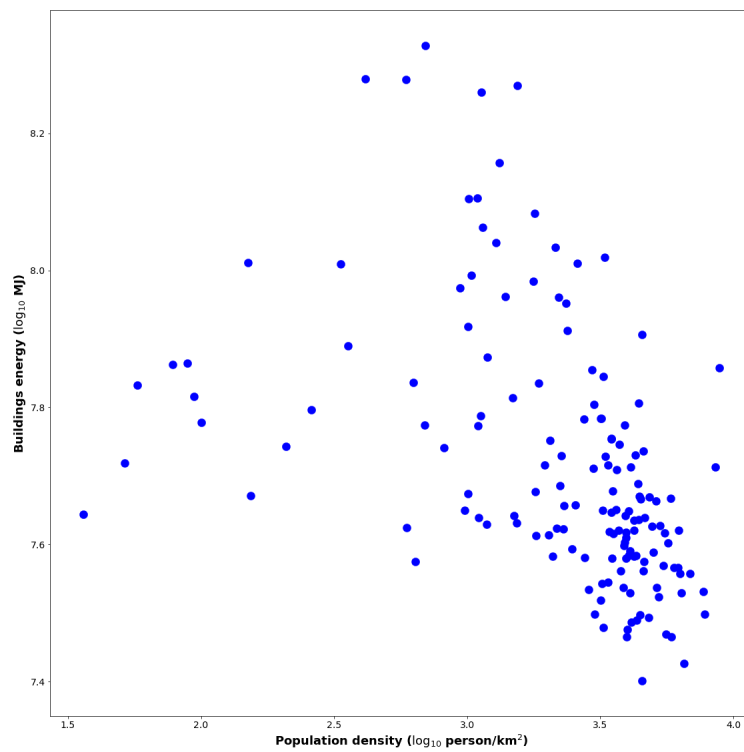
5-30a) and Figure 5-31b shows no clear trend. A possible reason may be related to the relative small proportion of commute transport – less than 9% on average – in the total energy consumption which can mask its influence on the grand total.

The multiple trends shown in Figures 5-30 and 5-31 demonstrates a wide spread of correlation values for both buildings and commute transport energy consumption and for both LAs. As the Pearson correlation is used in this research, the strength of correlation is measured between 1 and -1, expressing positive and negative relationship, respectively (Walker 2010). The closer the correlation value is to any of those values, the stronger is the relationship. Furthermore, all the correlations obtained in this work are significant since the probability levels (given by *p-value*) are lower than 0.05, though differences are observed for the many urban variables. Accordingly, the smaller the *p-value*, the more significant the relationship (Walker 2010).

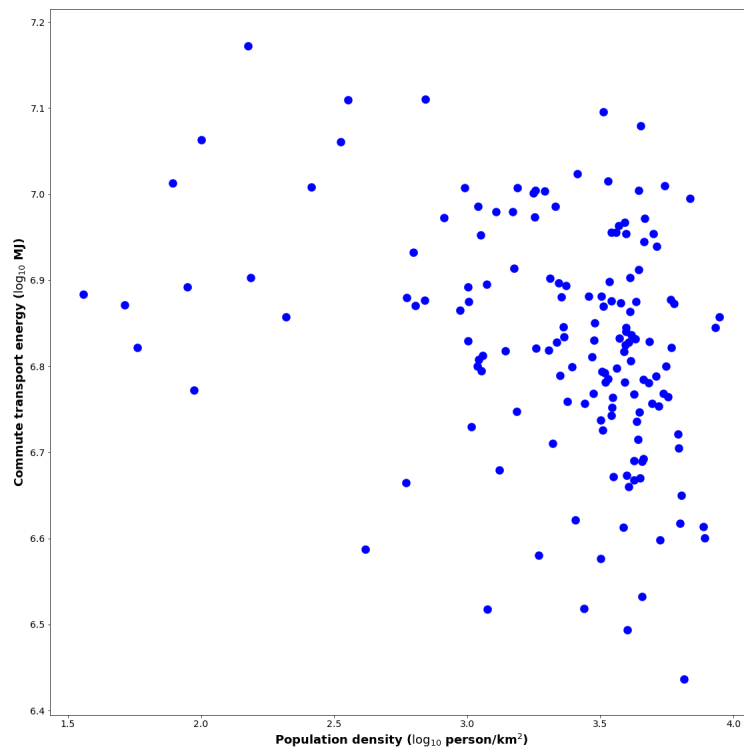
The negative correlation between energy consumption and population density is stronger for buildings than transport, and more for a new LA (Milton Keynes) than an old one with correlation coefficients of -0.45 (Figure 5-30a) and -0.38 (Figure 5-30a), respectively. Similar behaviour is observed for other LAs (for example: Bristol and Liverpool): multiple trends for the relationship between buildings energy and population density, though showing overall moderate correlation strength. In contrast, the relationship between transport energy and population density is not observed at all for Plymouth – coefficient value of -0.08 (Figure 5-31b) – and for Milton Keynes is not strong either (-0.31) (Figure 5-30b). Other LAs (for example: Manchester and Coventry) demonstrate identical tendency to Plymouth: unobserved relationship between transport energy and population density, expressed by the small correlation coefficient value. This reveals that commute transport in these LAs is not directly influenced by population density, which indicate poorer energy efficiency of transport and demonstrate the need for actions to improve it. Moreover, other urban variables, such as perimeter (variable 1) and dwellings density (22), also show multiple correlation trends. On the other hand, other variables (e.g. green space, 16, and household income, 32) show no correlation trend at all, i.e. it is not possible to estimate a fit of the correlation values of the relationship between those variables and energy consumption by LSOA unit.

5.3.2.3 Correlation for the LSOA units

In addition to the graphical outputs to demonstrate the goodness of the fit of energy consumption with urban form variables, Pearson's product-moment correlation was also obtained for all variables listed on Table 5.3. Figure 5-32 shows the values of correlation for

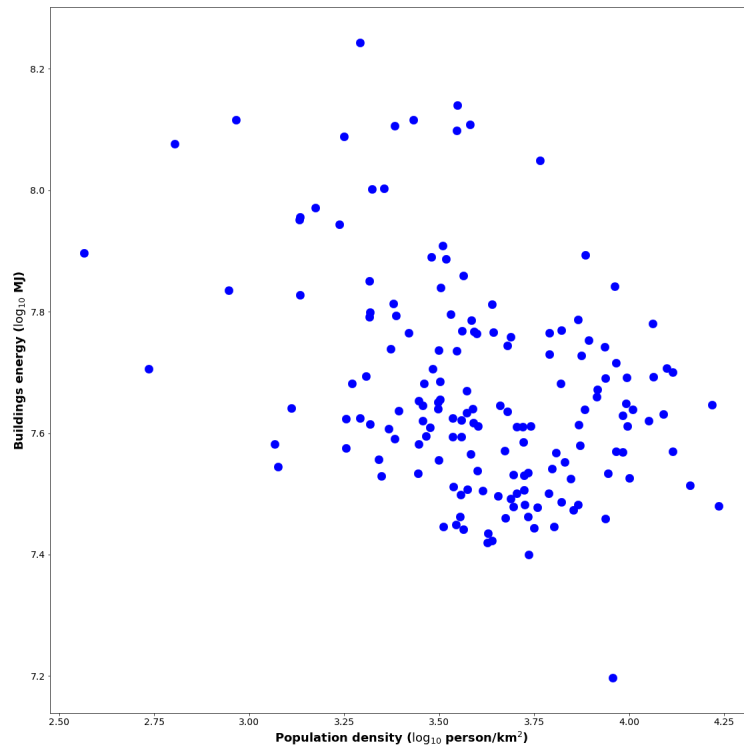


(a) Buildings

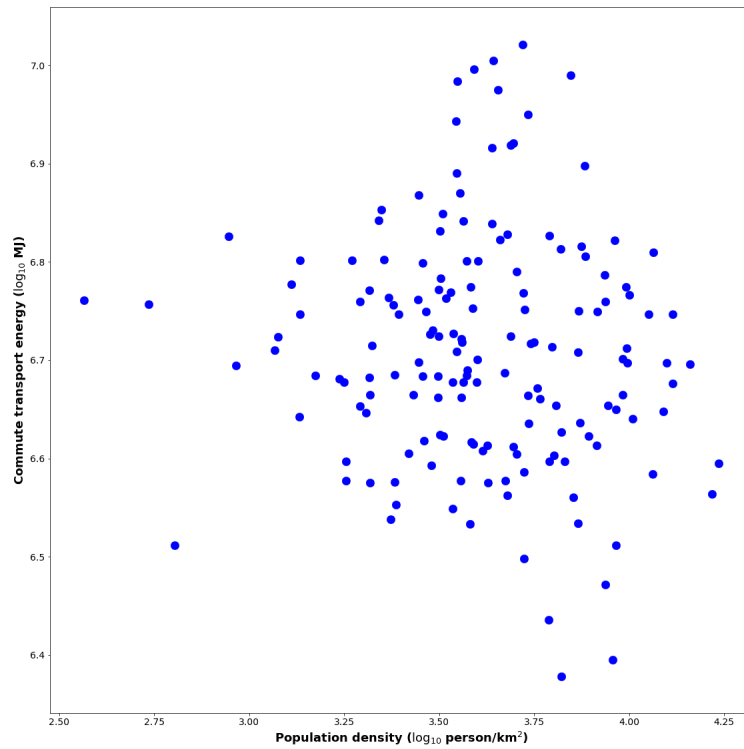


(b) Commute transport

Figure 5-30: Relationship between sectorial energy consumption and population density for Milton Keynes by LSOA level.



(a) Buildings



(b) Commute transport

Figure 5-31: Relationship between sectorial energy consumption and population density for Plymouth by LSOA level.

the different variables for the total energy consumption mapped in Figure 5-7 on page 83. The plot show that only about 37% of the variables reveal significant correlation strength, i.e. values $> |0.3|$. Furthermore, the correlation values support the compact city theory and other literature (Newman & Kenworthy 1989, Næss 2012): higher densities result in lower energy consumption, and thus better energy efficiency. Therefore, negative correlations between energy and density variables, such as population density (variable 19), dwellings density (22) and density of household spaces (24) are observed. On the opposite, positive correlation values are recognized for variables associated with the size of the cities/urban areas, such as surface area (2), extent of non-built-up area (12) and perimeter (1). Table 5.4 sums up the direction and strength of correlation for all urban form variables in relation with energy consumption.

Table 5.4: Correlation strength and direction of the urban variables (and respective ID as in Table 5.3) for their relation with the total energy consumption by LSOA in England.

DIRECTION	STRENGTH		
	Strong	Weak	None
Positive	1: Perimeter of the geographical unit 2: Surface area 12: Extent of non-built-up area 13: Ratio of open space 17: Resident population 21: Number of dwellings 23: Number of household spaces	3: Area of domestic buildings 4: Area of road network 5: Road length 6: Density of road length 7: Area of railway 8: Extent of built-up area 10: Area of buildings 14: Proportion of detached dwellings 18: Male resident population ratio 28: Proportion of population in employment 32: Yearly household income	15: Proportion of semi-detached dwellings 16: Green space 26: Private car availability per 1000 inhabitants 27: Proportion of population with higher education 31: Ratio of detached houses per flat
Negative	9: Proportion of built-up area 11: Proportion of area of buildings 19: Population density 22: Dwellings density 24: Density of household spaces	29: Proportion of population employed in services	20: Population density in built-up area 25: Density of household spaces in built-up area 30: Proportion of flats in commercial building

5.3.2.4 Looking at buildings and transport by LSOA

The analysis of correlation coefficients by sectorial energy (Figures 5-33 and 5-34) shows both similarities (in the case of buildings) and differences (for commute transport) with the total energy consumption. Accordingly, for only about 35% of the urban variables, energy consumption of buildings shows moderate correlation strength (positive or negative relationship), including density and size variables (e.g. variables 2, 19 and 22). For the remaining variables, buildings energy display no significant correlation (Figure 5-33). On the other hand, transport energy consumption reveals strong correlation with about 19% of the variables, which include population density (19) and surface area (2). If combined with moderate correlation strength variables, energy consumption of transport demonstrates significant correlation with more than 40% of the urban variables (Figure 5-34).

Considering that the variables showing significant positive or negative correlation for both

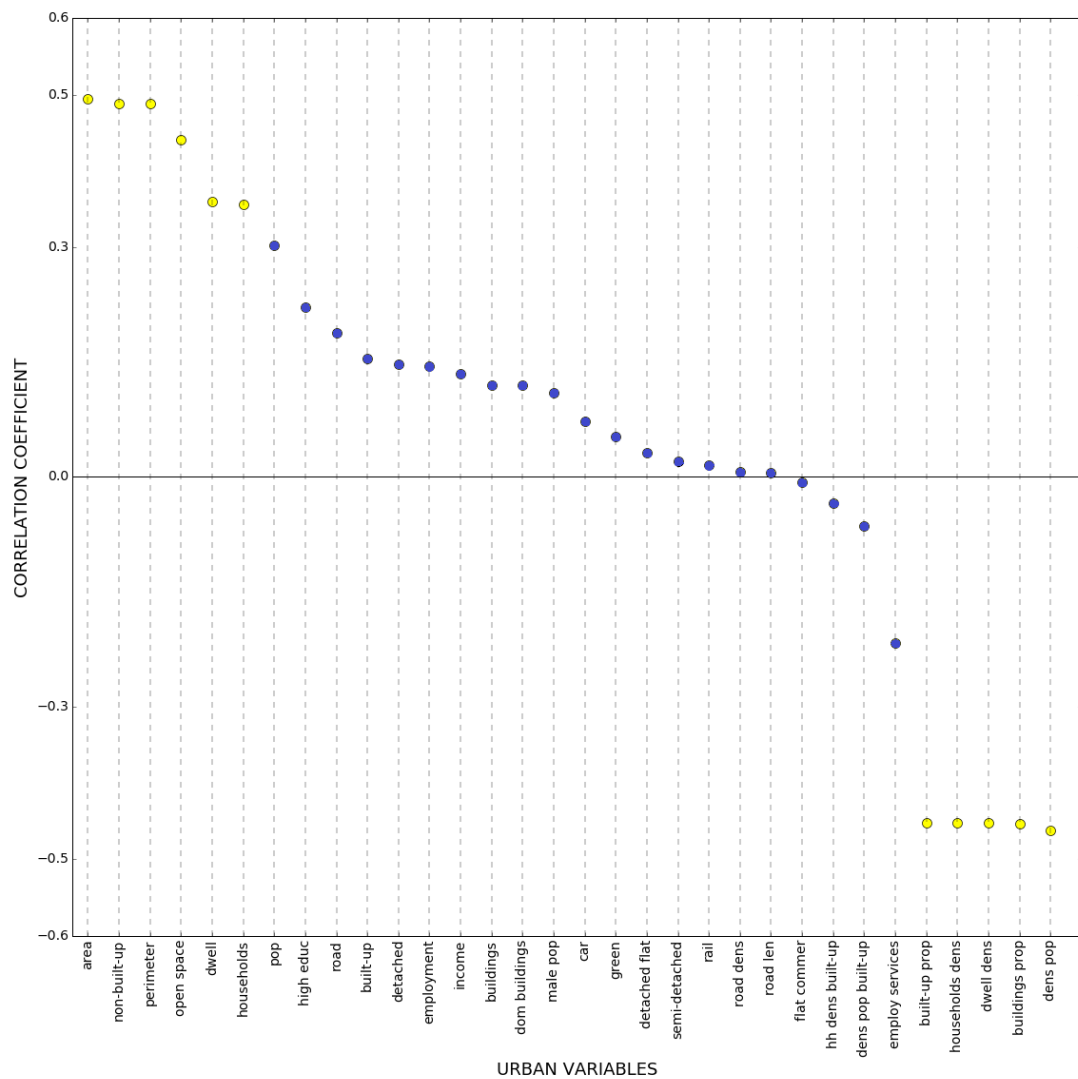


Figure 5-32: Correlation by urban form variable for the total energy consumption by LSOA in England, arranged by value. Blue circles: small correlation strength; Yellow circles: moderate correlation strength – Table 5.3 for the key to urban form variables.

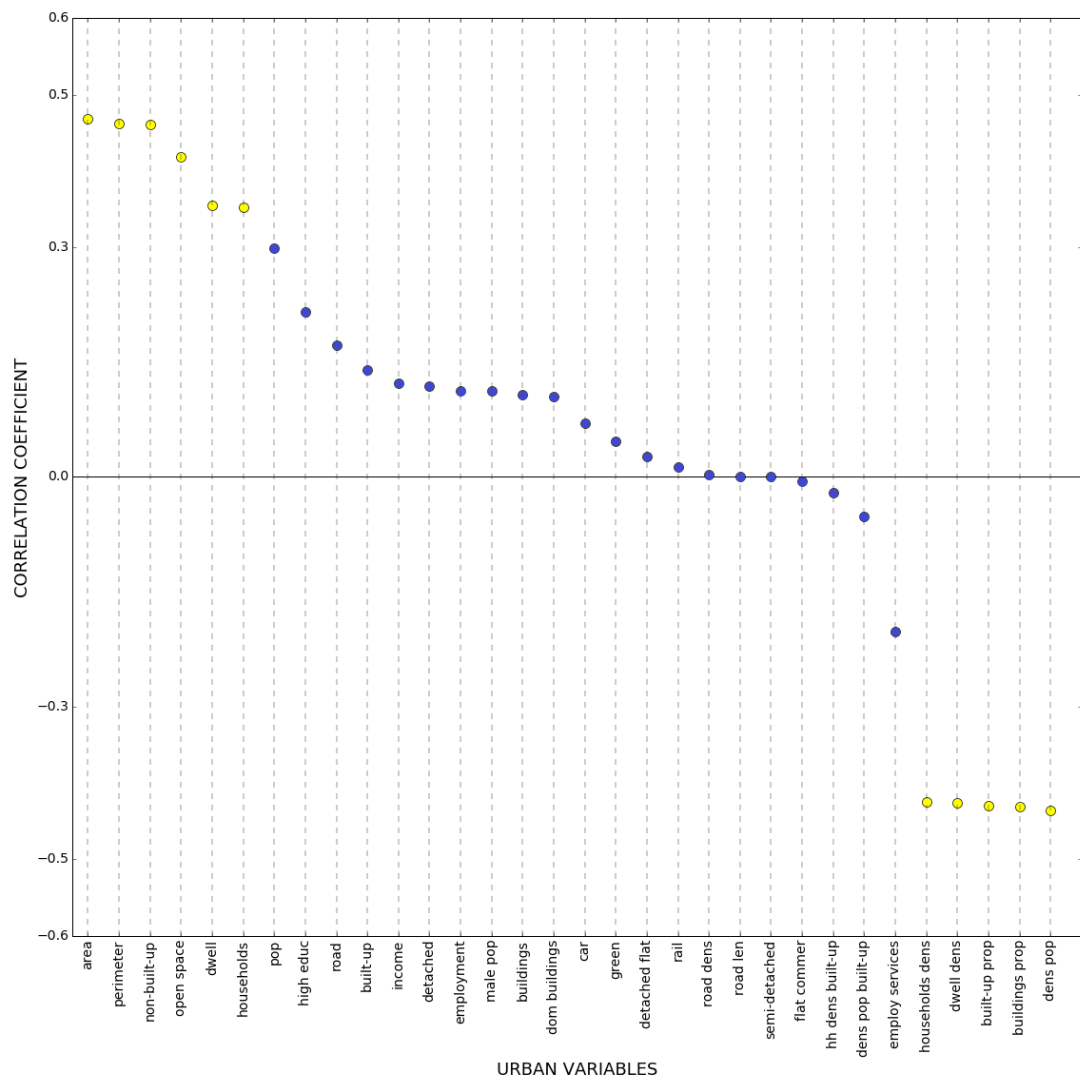


Figure 5-33: Correlation by urban form variable for the energy consumption of buildings by LSOA in England, arranged by value. Blue circles: small correlation strength; Yellow circles: moderate correlation strength; Red circles: strong correlation strength – Table 5.3 for the key to urban form variables.

buildings and transport energy are related to density and size, these findings reveal that the compact city theory is partially supported, i.e. the increase of population density results in lower energy consumption. However, this is mostly valid for commute transport energy (and not even completely), but not for buildings. Additionally, the majority of the variables have lower correlation coefficients, and thus not very strong relationship with energy consumption. Overall, the analysis of Figures, 5-32, 5-33 and 5-34 shows that only a few urban variables have significant impact on energy. Therefore, this is important for future

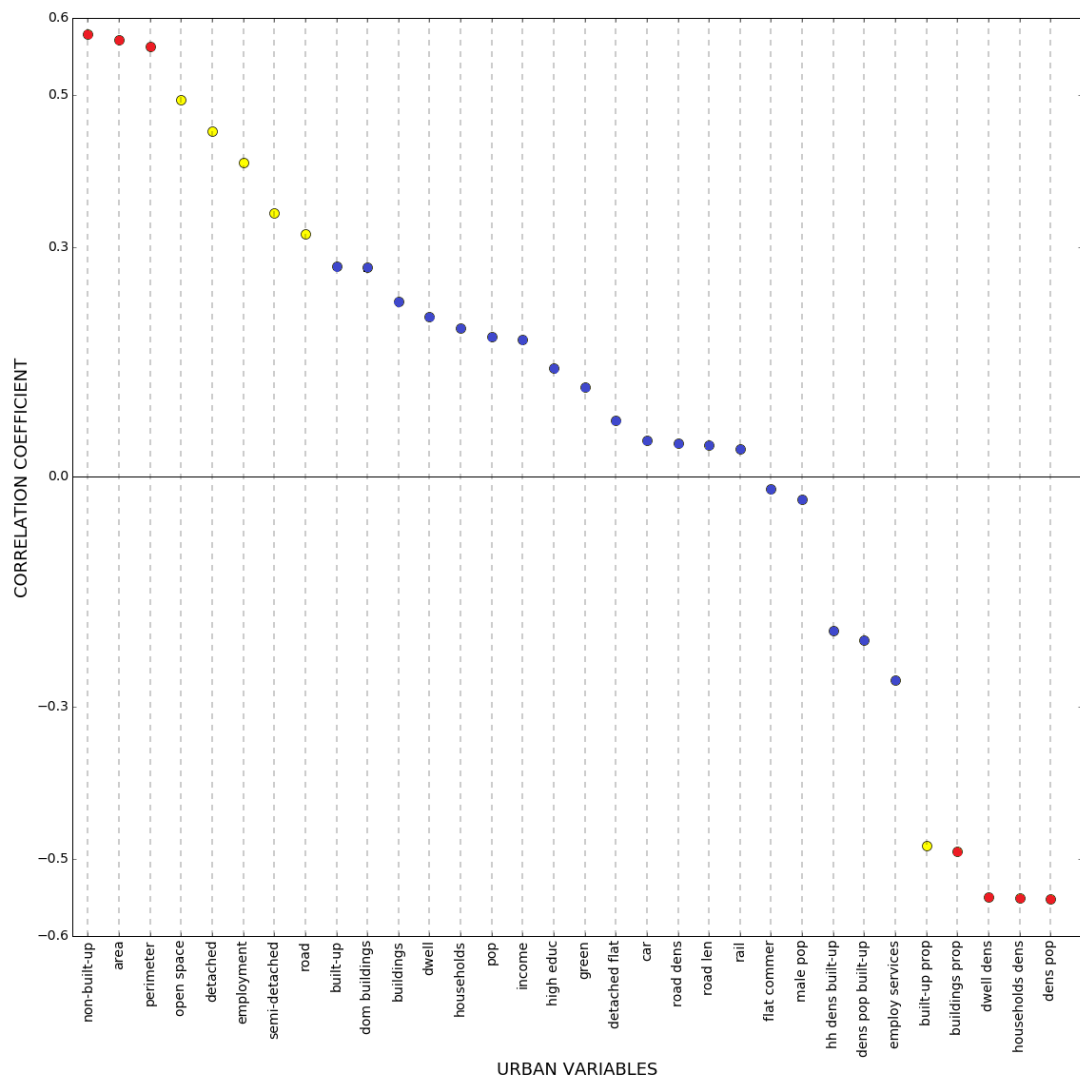


Figure 5-34: Correlation by urban form variable for the energy consumption of commute transport by LSOA in England, arranged by value. Blue circles: small correlation strength; Yellow circles: moderate correlation strength; Red circles: strong correlation strength – Table 5.3 for the key to urban form variables.

studies and for planners and policymakers, as research to reduce carbon-related energy consumption can be focused only on a selected number of urban variables.

5.3.2.5 Correlation for LAs

Figure 5-35 shows the correlation coefficients of the relationship between energy consumption and the urban form variables for 12 selected Local Authorities (LAs) in England. It

is clear that the City of Westminster is different from the remaining cities due to specific characteristics. This is demonstrated by the higher correlation values established between total energy consumption and the majority of the urban variables. Another LA showing significant dissimilarities with the remaining is Bradford given the higher values of correlation coefficients for most of the variables. However, with the exception of these two LAs, it is not identified a correlation trend based on the location or the characteristics of the 12 LAs.

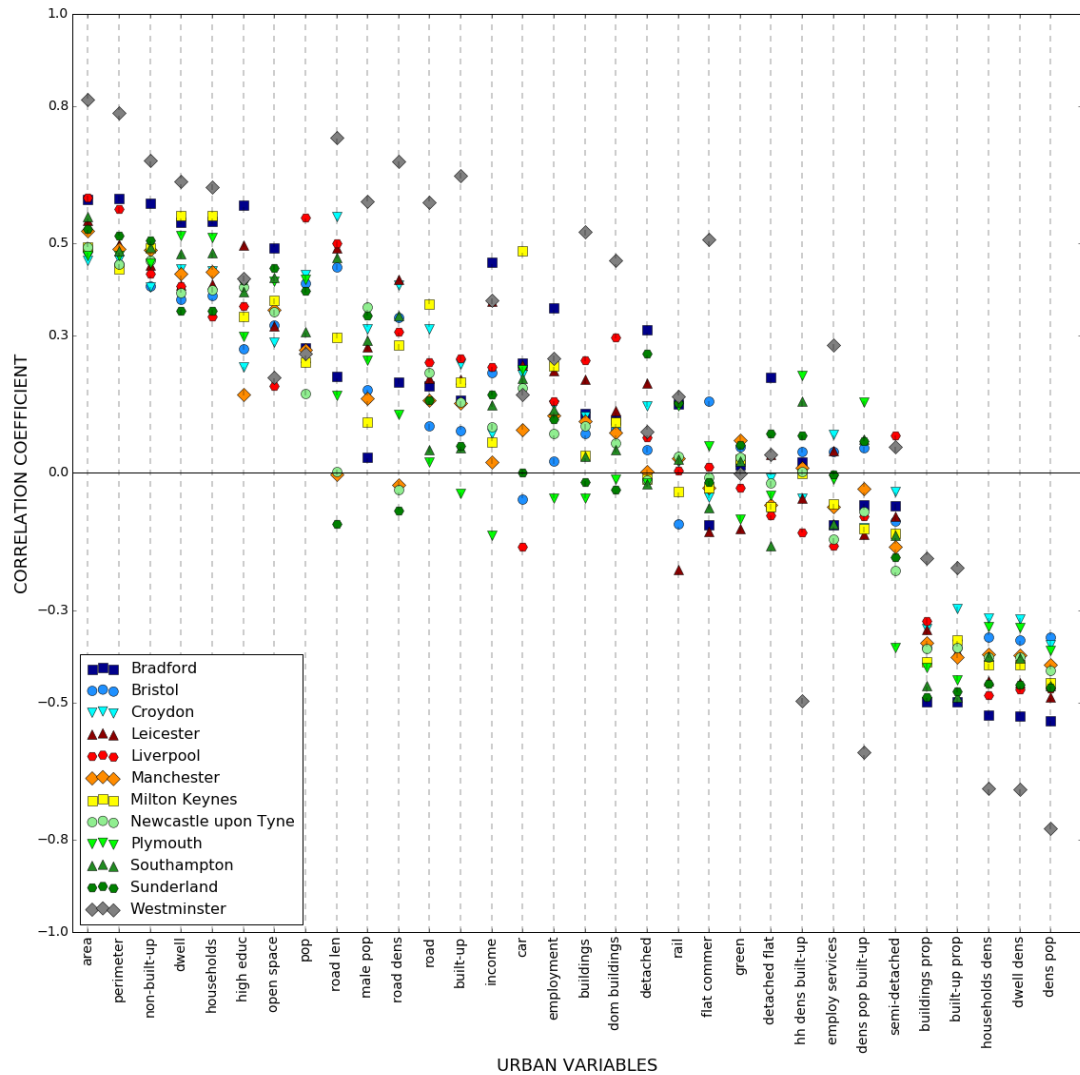


Figure 5-35: Correlation by urban form variable for the total energy consumption of selected LAs in England, arranged by value – Key to urban form variables in Table 5.3.

Figure 5-35 also shows that, except for Bristol and Newcastle upon Tyne, a few strong cor-

related variables are found for all LAs in regard to total energy consumption, mostly related to density and size characteristics, such as variables 2 (surface area) and 19 (population density). Although energy consumption has moderate to small correlation strength for the majority of the variables in all LAs (except Westminster), this reveals different results from Figures 5-32, 5-33 and 5-34 concerning the whole LSOA dataset, where strong correlations are almost non-existent. Therefore, the analysis by LA is very important to distinguish the individual characteristics of every location. Furthermore, by using a LSOA geographic level for the analysis, it is possible to compare the correlation values of the urban variables for all LAs to understand which characteristics influence energy consumption on each LA. This provides planners and policymakers with more information about the urban energy system to be used in strategies to better manage and reduce carbon-related energy use.

5.3.2.6 Correlation for land use clusters

The analysis by land use clusters also shows new insights. Figure 5-36 shows that the correlation strength varies with land use typology, meaning that urban development influences energy consumption and efficiency. Many variables demonstrate weak or no correlation with total energy consumption in each land use cluster, but stronger relationships are found for Cluster 9 (forest lands) with the majority of the coefficient values $> |0.5|$. Though some correlations are expected, as the increase of energy consumption with population growth (variable 17), it is important to emphasize the negative correlation of Cluster 9 with green space (16). This is different for the remaining land use clusters, as no correlation is observed, disagreeing with the common idea that increasing green area results in lower energy consumption. On that account, this new information shows that the strategies to reduce energy consumption in urban spaces should go further than suggesting the enlargement of greenspace.

Further analysis of Figure 5-36 reveals that the compact city theory, which argues in favour of higher densities to produce lower consumption, is not entirely demonstrated. In fact, the more urbanized Clusters (1 to 3) show weak correlation between energy and population density (variable 19); only Clusters 4, 5 and 8 show moderate correlation strength, expressing a negative relationship. Therefore, the results reveal that increasing population density in already highly urban areas will not produce better energy efficiency. At the same time, in the outlying suburb areas (here considered as cluster 4 and 5), the improvement of efficiency may be achieved if density is increased, given the moderate correlation strength. This contrasts with some research arguing that suburbanization and urban sprawl generates more energy consumption and household carbon footprint, thus suggesting compact city

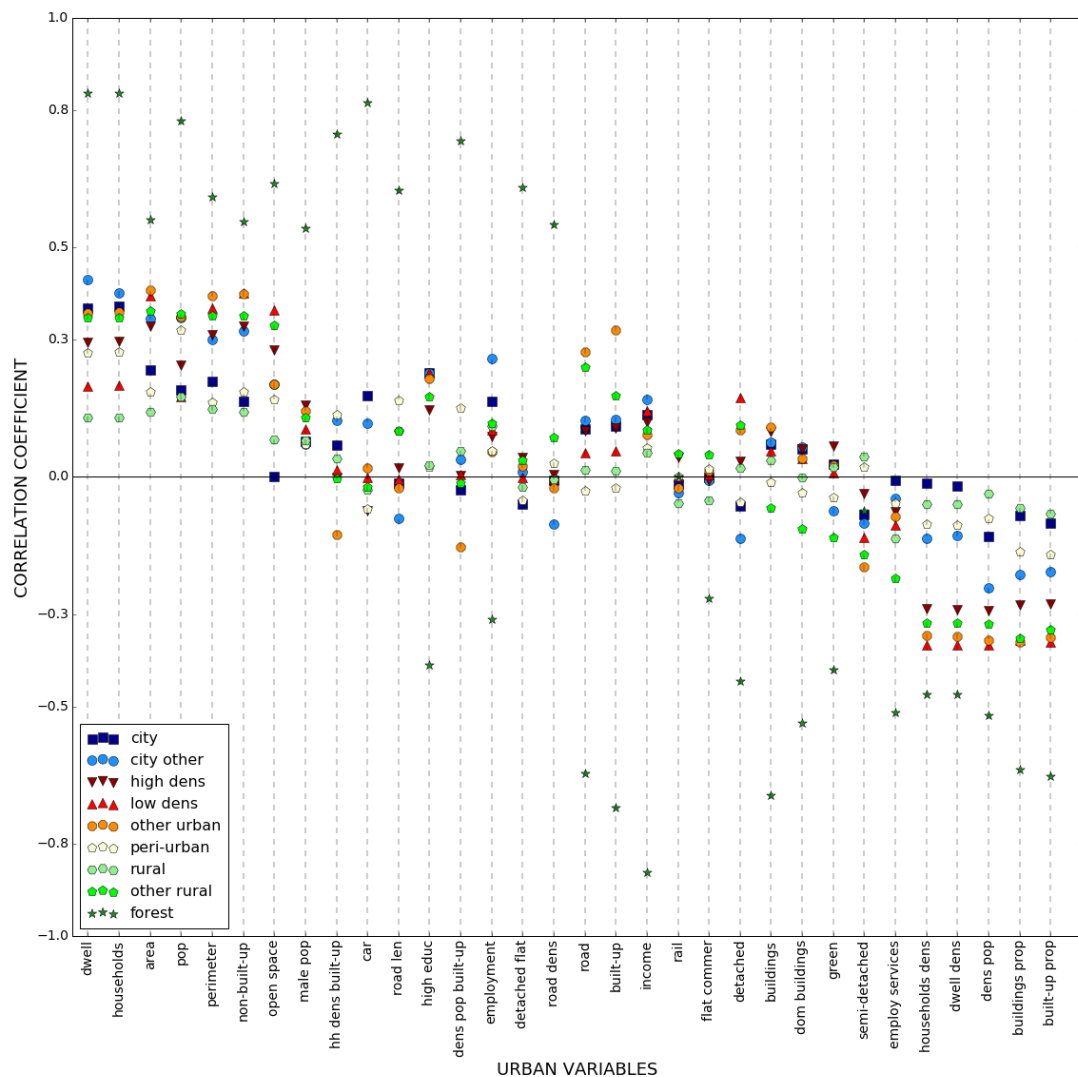


Figure 5-36: Correlation by urban form variable for the total energy consumption by land use clusters in England and at LSOA level, arranged by value – Table 5.3 for the key to urban form variables.

development (Creutzig et al. 2015, Jones & Kammen 2014, Kennedy et al. 2015).

Other significant results from the analysis of Figure 5-36 are the weak or no correlation of energy consumption with the proportion of population with higher education (variable 29) for all land use clusters (except Cluster 9). This also contrasts with some previous research referring to more environmental friendly behaviours adopted by individuals with higher levels of education (Virkki-Hatakka et al. 2013, Longhi 2015). Other variables (3 and 10), demonstrate also that energy consumption is not much influenced by the area of

buildings (total and residential), as no correlation is observed (Figure 5-36).

5.3.2.7 Looking at buildings and transport by land use clusters

A sectorial analysis of the energy consumption by land use clusters (Figures 5-37 and 5-38) shows significant dissimilarities with the previous Figure 5-36. In general, correlations are stronger for commute transport energy and many urban variables (i.e. coefficient values above 0.3) than for buildings' consumption, which has a resemblance with the total energy consumption. Moreover, despite of what is found for total energy, the main urbanized areas (Clusters 1 to 5), thus with higher densities, show moderate strength correlations and negative tendency between energy consumption for transport and density variables such as *19* and *2*. In contrast, buildings follow the same behaviour as total energy: the more urbanized and densely populated areas (Clusters 1 to 3) reveal weak or non-existent correlations with density variables, and only the suburb-like land use clusters (4 and 5) show moderate negative relationship strength.

5.3.2.8 Summary

The results of the correlations between energy consumption and urban variables demonstrate significant information that can be summarized by the following:

1. variables showing weak or no correlation, such as green space (variable *16*), area of buildings (*10*) and proportion of flats in commercial building (*30*), suggest not to be suitable to study energy consumption in urban spaces;
2. correlation values differ according to the scale of analysis, i.e. overall LSOA dataset, regions, LAs and land use clusters, as well as sectorial analysis;
3. the Greater London region demonstrates better energy efficiency;
4. sectorial analysis usually displays multiple correlation trends for many variables and cities, especially for density variables;
5. less than 40% of the variables reveal significant correlation strength with energy;
6. correlation results partially support the compact city theory expressing that lower consumption is favoured by with higher densities, but different values are obtained for all LSOAs, LAs and land use clusters;

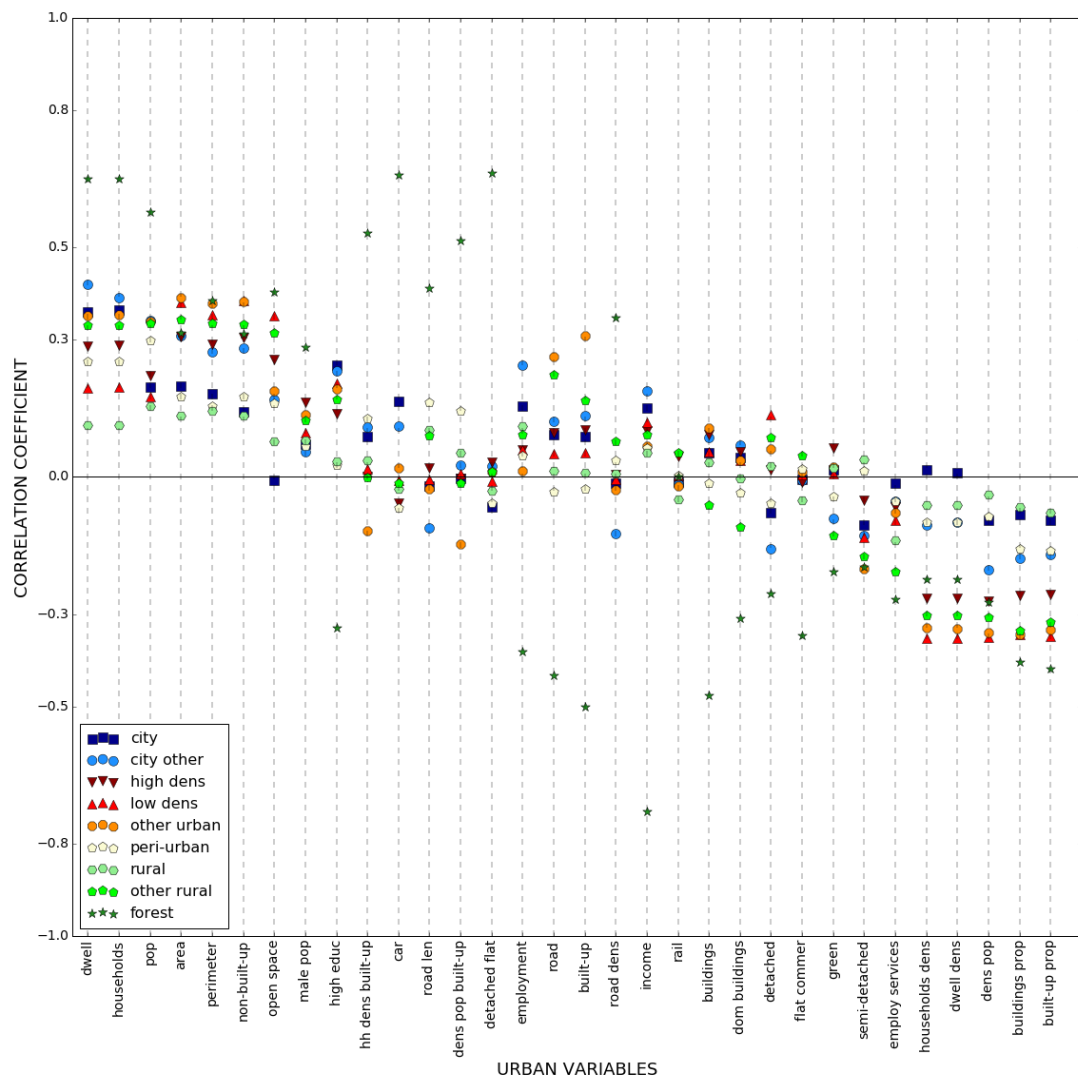


Figure 5-37: Correlation by urban form variable for the energy consumption of buildings by land use clusters in England and at LSOA level, arranged by value – Key to urban form variables in Table 5.3.

7. urban variables show stronger correlation with commute transport energy than buildings;
8. density and size variables reveal stronger correlation values than the remaining urban variables;
9. contrasting correlation values are found for all the land use clusters;
10. more environmental friendly behaviours adopted by individuals with higher levels of

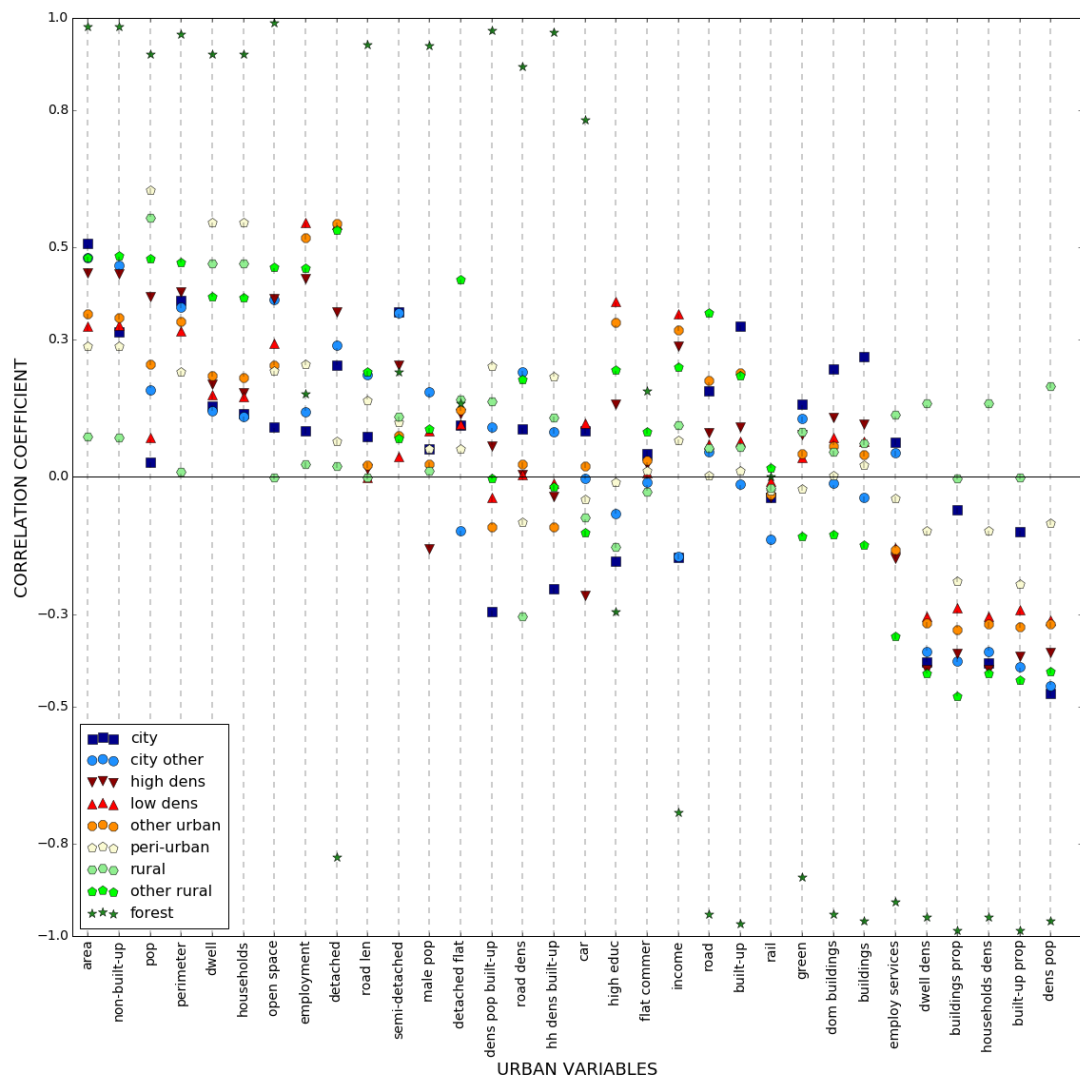


Figure 5-38: Correlation by urban form variable for the energy consumption of commute transport by land use clusters in England and at LSOA level, arranged by value – Key to urban form variables in Table 5.3.

education are not observed.

The contrasting results between this work and previous research reveal the importance of large scale analyses, as the finding of many small scale studies may not apply to high resolutions (Poumanyong & Kaneko 2010). In this way, the analysis demonstrates how the study of different cities, regions and countries, as well as the study at different geographical resolutions produce distinct outcomes (Shim et al. 2006), suggesting divergent planning actions. The variance of the relationship between urban variables and the different types of

energy also reveals the importance of focused planning strategies to achieve better results. This highlights the need of focused planning strategies that are based on more detailed analysis of the policy targets: regional planning should be different from local planning, as the targets and objectives have to be adapted according to the individual characteristics of each energy consumption. Planning and policymaking in England should not follow international trends and approaches that were applied to contrasting urban systems.

Chapter 6

Discussion and research value

The research presented here introduces a new understanding of the relationship between energy consumption and urban form characteristics by means of correlation and scaling laws analyses. This is preceded by the introduction of a simple energy use metric combining buildings and commute transport, and the identification of land use typologies at a large geographical scale of analysis. The discussion of the results for the three main stages of the work presented in the previous Chapter 5 follows.

6.1 The energy use metric

The energy use metric (Section 5.1) allows the identification of consumption patterns at LSOA level for all England. Therefore, considering Figure 5-7 in Section 5.1.3, it is revealed an overall lower per capita consumption in major cities and urban areas. In contrast, the North region of England, as well as much of the areas immediately outside the major urban centres, are less efficient, and so demonstrate higher per capita energy consumption. Such aspects corroborate the majority of the literature associating higher population densities found in urban areas with lower energy consumption, and therefore better energy efficiency (Newman & Kenworthy 1989, Neuman 2005, Amado et al. 2016). However, differences are observed between the individual energy consumption of buildings and transport, and the total consumption, validating the benefit of the combined energy use metric stated by Equation 4.2, which can result in more focused energy mitigation actions.

The analysis of the commute transport consumption alone (Figure 5-4 in section 5.1.2) demonstrates a better efficiency of transport in the Greater London region and in the

Liverpool-Manchester conurbation. For that reason, this agrees with some previous research suggesting the increase of population density to support energy savings in transport (Breheny 1995, Holden & Norland 2005, Newman & Kenworthy 1989). At the same time, the lower commuting transport energy consumption in the Greater London region draws attention to its good public transportation system, revealing how important that is to reduce the carbon footprint of commuting in the rest of the country.

The results of the energy use metric also shows the similarity between total energy consumption and the consumption for buildings alone (Figure 5-1), as well as that the average proportion of commute transport in the total consumption is about 9%. Although exceptions are observed, the impact of that transport energy on the whole consumption is smaller than the one obtained for buildings. Nevertheless, this 9% figure is higher than previous research (Lovelace 2014) – 4.1% at NUTS level 4 –, which may have been underestimating commute transport energy consumption. This underestimation draws attention to the use of (i) smaller scales of analysis and (ii) different methods to calculate commuting. As a consequence, studying energy consumption at more fine-grained scales (as LSOA) will deliver a better description of urban consumption to be used by policymakers in more focused energy reduction strategies.

Overall, the energy metric provides significant results on the consumption patterns in England at LSOA level, distinguishing the different consumption between cities and regions, as well as within city or Local Authority boundaries. Therefore, it is delivered essential information that can be used by planners and policymakers of local governments to outline more adjusted actions and policies based on the local energy consumption characteristics.

6.2 Obtaining land use typologies

Land use typologies were obtained at LSOA level, using cluster analysis and based on a large set of urban form variables (Section 5.2). This allows a better detailed identification of the urban boundaries that go further than the city limits. As defining the urban outer limits is one of the main challenges of research on energy (Burian et al. 2014, Masucci et al. 2015, Arcaute et al. 2016, Long 2016), land use typologies can later be used to acknowledge the internal energy consumption dynamics of urban areas. Therefore, the present work launches further development in the research of urban spaces and respective characterization.

6.2.1 Applying PCA and cluster analysis

Principal Component Analysis (PCA) was employed in section 5.2.1 to diminish the probability of collinearity between the variables and, simultaneously, simplify the following cluster analysis. By analysing the scree plot (Figure 5-9), the eigenvalues of the extracted factors and the observation of the “rule of the elbow”, it was found that 6 main factors explain the urban form variables dataset. This shows that a large dataset of variables may not be needed to characterize cities and urban areas, although it is important to identify which variables can better describe them from the resulting 6 main factors or dimensions.

The cluster analysis was applied in section 5.2.2 to the 6 dimensions of the urban form dataset arising from PCA. In this work, two types of cluster analysis were used to complement each other and produce better and reliable results: (i) hierarchical clustering, and (ii) k-means clustering.

The two graphical outputs – dendrogram and heights plot – resulting from the hierarchical clustering in section 5.2.2.1 allowed the definition of the optimal number of clusters of the dataset. The analysis of those outputs revealed that the collected information can be split into 2 outlier clusters and 7 to 8 principal clusters. This information was essential to use in k-means clustering in section 5.2.2.2. Consequently, the k-means clustering was then tested for 7 and 8 clusters. The consistency of the obtained clusters was validated using the silhouette width method. Furthermore, the proportions of each cluster, as well as the mapping of the cluster solutions, helped to determine and demonstrate the significance of the clusters calculated. These clusters translate the land use typologies at LSOA level in England.

The application of cluster analysis put forward the problem of defining the optimal number of clusters k . The problem has occupied many researchers (Jain & Dubes 1988, Brock et al. 2008, Steinley 2006), but no final solution has been achieved, as the appropriate number of clusters often depends also of the analysed dataset. In this research, some actions were taken to overcome the difficulties and ensure more reliable results. First of all the use of two types of clustering so that one validates the other. Moreover, each analysis was examined considering different graphical outputs, statistical values and approaches followed by previous studies. Additionally, the mapping of the different options for optimal number of clusters k helped to verify the sensibility and consistency of the outcomes in the real world. Therefore, the final number of clusters (9) is considered a solid, balanced and reliable result to be used to study the relationship between energy and urban form. Future work may include the use of different urban form variables, validation procedures or distinct clustering methods.

6.2.2 Results of cluster analysis

In section 5.2.3 the final results of the cluster analysis describe the land use in England. The analysis of Figure 5-17 shows mostly a rural North region and an urban system composed by main city centres, surrounding high and low density urban areas (i.e. suburbs) and transition peri-urban/rural spaces forming a ring around the previous. These transition areas seemingly emerge as buffer zones that prevent the advance of urbanisation and keeps rural and countryside spaces from being exploited. Though nowadays agricultural and other farming activities of the primary sector do not require large pieces of land, the damaging and the reduction of rural areas brings various environmental and social negative consequences. These impacts would later be experienced in urban areas, putting pressure on populations and their economic, social and health conditions. Therefore, the identification of land use boundaries provided by the cluster analysis provides important information to planners and policymakers that can observe the expansion of urbanisation and restrain abuse, and thus avoid the mentioned negative effects that would be faced in both rural and urban areas.

A designation of the land use typologies resulting from the cluster analysis is introduced in Table 5.2 (see page 96). Although based on the simplification of standard classification systems, which often leave ambiguous interpretation of the areas in terms of function and use (Nel et al. 2017), the naming of the land use clusters in this work is simple and seeks to be applied in the study of the relationship between energy consumption and urban variables. Therefore, Clusters 1 to 2 are assumed to be the major urban areas and clusters 3 to 6 reflect suburbs and transition areas of urbanisation. The identification of land use typologies at LSOA level reveal the distinction of urban development within cities and between them. This shows the internal and external dynamics of the urbanisation in England, providing local councils with new information about that process. Overall, the identification of land use typologies delivers new knowledge about the urban system in England.

6.3 Analysis of the relationship between energy and urban form

The relationship between the energy consumption given by the new energy use metric and the urban form variables (including the land use typologies) was studied applying two analyses: (i) correlation and (ii) scaling laws dependencies. A detailed discussion of the two analyses follows.

6.3.1 Scaling relationships

Scaling laws were explored in section 5.3.1 to understand the influence of these urban variables on energy consumption, covering the whole LSOA dataset, selected Local Authorities (LAs) and land use clusters or typologies. The results of scaling show a prevalence of sublinear behaviour for the majority of the urban variables in relation to energy (Figure 5-20). This suggests that energy consumption essentially abides to the economy of scale, similarly to what is found for largest cities that require less infrastructure as population increases (Bettencourt 2013, Cottineau et al. 2016). The analysis also reveals that many density variables, as well as proportion-related ones, do not express a linear relationship with energy consumption.

The prevalence of sublinear scaling, as well as a significant number of inverse scaling relationships, is also observed for a set of 12 LAs (Figure 5-23 in section 5.3.1.2). However, it is possible to distinguish differences between LAs. General tendencies seem to arise: for example, the larger number of linear and superlinear scaling variables for LAs located in the Greater London region. It is also revealed that the proportion of population employed in services (variable 29 in Table 5.3 on page 102) has a significant impact on the increase of energy consumption in the City of Westminster. This provides new knowledge about other variables influencing energy use, as most of the previous research has been mostly focused on the effects of population density in consumption, but not the job sector. Considering that the majority of services jobs are carried out in non-residential buildings, it is essential for policymakers and planners to target the improvement of the energy efficiency of these buildings, which will certainly mitigate the overall energy consumption of cities.

The analysis of scaling exponents of energy consumption for LAs with similar population sizes also reveals new understanding of their structure. It is shown a contrasting scaling behaviour of some urban variables between those LAs with similar populations, but different historical occupation, such as between Milton Keynes ('new city') and Plymouth ('historical city'). Therefore, new LAs seem more car dependent, given the superlinear scaling of car availability (variable 26 in Table 5.3), comparing with the superlinearity of the resident population variable (17) for historical LAs, so more population dependent. Car dependency in Milton Keynes can be linked to the insufficient or inadequate public transportation service, meaning that a small increase of car availability will result in significant impact on energy consumption. On the other hand, the superlinear scaling of population in Plymouth demonstrates that the growth of that variable produces bigger effect on consumption, given the reliance of the economic development of historical LAs on population increase. Other differences are not recognised between new and historical LAs, or among the remaining 12

LAs in Figure 5-23, apart from the prevalence of sublinear scaling of energy consumption for most urban variables.

The results of the power-law scaling relationships for the land use typologies or clusters in section 5.3.1.4 show that scaling exponents vary considerably. Although an overall prevalence of sublinear scaling is observed, the clusters show differences between among them (Figure 5-25). For instance, land use typologies considered “outliers” – Clusters 8 and 9 – demonstrate more prevalence of inverse scaling. This argues in favour of their “outlier” condition, as a lower number of urban variables influences energy consumption in the areas covered by these clusters.

Other scaling behaviour differences are observed between clusters, such as the contrast between Clusters 1-2 and 3-4, i.e. between the main city areas and the suburban surrounding spaces. The differences are essentially related to density variables, which reveal that the increase of population density in already highly urbanized areas (Clusters 1-2) will not result in lower consumption. Actual impacts may only be produced in suburban/transition areas (Clusters 3-4). Furthermore, the superlinear scaling behaviour of urban variables such as the number of dwellings and household spaces, expressed by Cluster 3, demonstrate that achieving energy efficiency should be based on the rise of population density in these areas.

In section 5.3.1.4, it is also acknowledged that bigger impacts on energy consumption for land use clusters are mostly associated with socio-economic variables. Though complying with sublinear behaviour as the remaining variables, those socio-economic variables reveal higher scaling exponent values (usually above 0.5). In contrast, physical or landscape variables such as road length and proportion of built-area have less influence over energy consumption. This differs from urban sprawl theories that say that the biggest effect on energy demand is by infrastructures (Ewing 2008, Cox & Utt 2004, Kennedy et al. 2015), and so brings new information to policymakers and planners seeking to mitigate carbon-related energy consumption. Consequently, it is expected that targeting socio-economic characteristics will produce more impacts on the overall reduction of energy use than physical variables. Additionally, the variance of scaling behaviours between land use clusters shows the importance of understanding the stage of development of urban areas prior any policymaking or implementing actions. In general, the sublinear scaling found for the majority of the urban variables agrees with most literature (Rybski et al. 2016, Fragkias et al. 2013), but expands the knowledge to other urban form variables.

6.3.2 Looking at the correlations

The correlation between energy consumption and urban form variables was also studied in section 5.3.2 and shows that total energy consumption has moderate relationship strength with almost 40% of the urban variables. However, significant differences are identified between land use typologies, Local Authorities (LAs), regions and the whole LSOA set. This set reveals that energy consumption has moderate negative correlation with much of the density variables (such as population density), and conversely with size-related variables (e.g. total surface area) (Figure 5-32 on page 120). This generally supports findings from previous studies, as well as backing up the compact city theory, i.e. lower energy consumption is favoured by higher density areas. Still, the obtained correlation values are of average intensity, making way to find dissimilarities among regions and cities.

In section 5.3.2.1, Figure 5-29 shows some distinction between regions: in general, Greater London has the largest energy consumption of all regions, but it is also more energy efficient in relation to population density. This means that the increase of density values would produce better efficiency, as argued by compact city theorists. Nevertheless, this is not valid for all regions, showing that many other urban variables have an effect on energy consumption. For example, for the whole LSOA dataset, two trends can be seen for the relationship between energy and population density (Figure 5-27), showing that the analysis of consumption cannot be reduced to a few variables and requires more detailed examination.

The analysis for LAs with similar population-size in section 5.3.2.2 reveals new insights: multiple correlation trends are observed between the total energy consumption and some urban variables. Additionally, stronger relationships are found between population density and energy of commute transport than of buildings. Further analysis shows different correlation values of the urban variables between historical and new LAs, as well as between large and smaller areas. However, a general tendency to distinguish those LAs is not found: correlation significance seems not to be associated with area or population size, or historical occupation. Moreover, the weaker correlation strengths between commute transport energy and, for example, density variables show that the increases of density does not result in lower consumption, and so energy efficiency actions for transport should be put into practice.

The analysis of the correlation between energy and urban variables by land use typology in section 5.3.2.6 demonstrates some significant outcomes. First related to the compact city principles: the increase of population density (and other density variables) will not result in obvious lower energy consumption, and subsequent better energy efficiency, if applied to

already highly urbanized areas. This is expressed by the weak correlation strength between energy and density variables of Clusters 1-3 (Figure 5-36). In contrast, outlying areas as Clusters 4 and 5 – suburban ring spaces surrounding cities – still show the possibility of improving their energy efficiency by the rise of density due to the moderate correlation between energy and the urban variables. This differs from urban sprawl theories (Ewing 2008, Cox & Utt 2004, Brody 2013) that argue about the growth of energy consumption with the continuous suburbanization process. Furthermore, the correlation results by land use clusters reveal small impact of green space on the decrease of energy consumption: except for Cluster 9, all the remaining clusters show no correlation between energy and green areas. This contrasts with environmental theories in favour of increasing green areas to achieve lower energy consumption. Although the decrease of green areas brings negative consequences such as social stress and decrease of air quality (not studied in this thesis), the results in section 5.3.2.6 show no direct connection between green spaces and energy consumption in urban areas.

Additional findings are shown for the analysis of correlation by land use clusters or typologies in section 5.3.2.7. For example, it is revealed that the footprint area of buildings does not have a significant effect on energy consumption, as the correlation coefficients are weak for all clusters. The insignificant correlation values for the proportion of population with higher education (variable 29 in Table 5.3) also show that the impact of education to create more environmentally friendly behaviours is not observed. Thus, although household behaviour has been mentioned by some literature (Virkki-Hatakka et al. 2013, Longhi 2015) as a way to achieve better energy efficiency, the results in this research show differently.

6.3.3 Summary of correlation and scaling laws for clusters

Taking everything into account, i.e. the analysis of correlation and the scaling dependencies between energy and urban variables by land use typologies show that these can be combined into: (i) Clusters 1-2, demonstrating the principal cities/urban areas; (ii) Clusters 3-5, covering the suburban ring areas; (iii) Cluster 6, comprising mainly transition areas; and (iv) Clusters 7-9, primarily the rural and agricultural spaces. The more significant correlation differences are identified between these main cluster major groups. Therefore, Clusters 1-2 show that density variables have smaller effect on energy consumption, which contrasts with what is found for Clusters 3-5. Additionally, size-related variables, such as the footprint area of buildings or green space, show little impact on the final consumption for all clusters. The results for household behaviour also reveal that there is a long way of improvement to achieve better energy efficiency of residential buildings. In general, the different correlation

values between land use clusters or typologies for the many urban variables demonstrate the need of developing more focused and oriented analysis, planning and policymaking, to adapt strategies and objectives to the local characteristics of the target areas. Therefore, this adjustment should consider the land use typology and the use of a broader dataset of urban variables to get a better characterization of each area.

6.4 Limitations of the work

A research work of this scale – the LSOA dataset alone covers 32,844 units – had to be structured by making some compromises. Simultaneously, the published statistical information includes limitations, as data is based on estimates of energy consumption, commute travels, etc. Furthermore, the application of the results from this research does not consider all aspects of urban areas. Therefore, it is essential to draw the attention to the constraints of the work.

6.4.1 Information limitations

One of the first constraints of the research is about the available information. The energy use metric uses readily available data. This offers local authorities the chance to replicate the metric, but restricts them to that published information. Furthermore, not all information is available at LSOA level, forcing the application of a downscaling procedure to adjust the original data to LSOA. Though the impact of downscaling is minimized by the use of a satisfactory scaling factor and a validation process (see section 4.1.2.4), differences between estimated and real world values are expected. Moreover, the energy use metric includes only the operational energy of buildings and commute transport, perceived as the main energy vectors over which local councils and urban planners may have more control or influence. For regional and nationwide energy strategies on carbon-related energy consumption reduction, a more complete outlook of consumption would be required. Additionally, although official and freely available information were used in this research, large datasets as Census data are usually 'messy' and some inaccurate or invalid records have been identified (Rae 2016).

The use of urban form to select the characteristics of cities and general urban areas is, at the same time, a limitation and an added value. First, because urban form covers a vast range of physical and socio-demographic characteristics that can describe cities and urban areas with much detail. Furthermore, the methodological approach used here allows the inclusion of

additional variables (there is virtually no restraint) to expand the characterization of urban spaces. On the other hand, the issues regarding the use of urban form is linked to the fact that there isn't a standard, predetermined definition of urban form (Schwarz 2010, Frenkel & Ashkenazi 2008, Schneider & Woodcock 2008). In this work, this restriction is compensated by selecting a large dataset of landscape and socio-economic variables. These variables consider a wider scope of the characteristics to describe cities and general urban areas. The use of a large set of variables allows incorporating the five physical dimensions of urban form – complexity, compactness, heterogeneity, density and centrality (Huang et al. 2007, Herold et al. 2002) –, as well as the inclusion of the effect of human behaviour and other social process in urban areas (Schirmer & Axhausen 2015, Lima 2001).

6.4.2 Excluded human factors

The results from the relationship between energy consumption and urban form variables essentially suggest the increase of population density (at least for Clusters 4-5, i.e. suburban areas) to achieve better energy efficiency. This has been proposed by previous studies (Newman & Kenworthy 1989, Breheny 1995, Neuman 2005), but generally those analyses do not include human perspectives such as well-being. In fact, the increase of density may result in an increase of air pollution, depletion of resources and reduce the overall environmental quality of life due to concentration of people (Chen et al. 2008, Melia et al. 2011). Moreover, the energy demand of buildings and related CO₂ emissions can increase with population growth (IEA 2011, BPIE 2011). In this research, the social, health, cultural and other consequences of the intensification of population density are not included, although socio-economic and demographic variables are included in the urban form metrics. Nonetheless, the collected dataset may not tell the whole story regarding urban systems, making way for the addition of further variables to the analysis. Consequently, it is important that future work covers in more detail the human perspective of the intensification strategies, as lower energy consumption may not correlate with better well-being.

6.4.3 Suggested improvements

The use of a LSOA resolution produced valuable insights and novel perspectives of the relationship between energy and urban characteristics. However, additional statistical and analytical tools may be applied to expand the understanding of that relationship. For example, further knowledge about that relationship can be acquired with the use of neural networks, multiple regression analysis, forecast models or cellular automata methods. Over-

all, the compiled dataset for this thesis presents itself as being of great value to research, given its resolution and the number of variables of both energy consumption and urban form. Therefore, expanding the analysis by applying different statistical approaches would provide additional information about the relationship energy and urban variables.

6.5 Application to planning

The research conducted in this thesis had mainly the objective of characterizing the patterns and behaviours of the relationship between energy consumption and a large dataset of urban variables. At the same time, the combined energy consumption patterns and the land use typologies at LSOA level were obtained. However, the results aim, ultimately, at providing new information to policymakers and planners that can be used to design strategies seeking to reduce carbon-related energy use. This section addresses likely applications of the results to planning.

6.5.1 Applying compact city

The overall results show that compact city theory should be favoured in yet unconsolidated urban areas (such as land use clusters 3 and 4), i.e. local governments should encourage the increase of, for example, population density to achieve better energy efficiency. This can be done by building new residential areas, but without overlooking the potential negative consequences of compactness, and so defining beforehand the limits of population growth. In contrast, in already densely populated areas that compactness should be avoided, and instead constrain density growth and improve the efficiency of, essentially, non-residential buildings and commute transport.

Other measures include, for example, retrofitting and the use of renewable energy and smart grid systems to obtain better energy efficiency for buildings and transport. The research also showed that socio-economic variables have more significant impact on the reduction of energy consumption than other variables. Therefore, energy mitigation actions should arise from the intervention on those variables to obtain better results.

6.5.2 Local scale analysis and land use

The results from the research also reveal the importance of local scale analysis, since different scaling and correlation values were found according to geographical scale and

location of cities and urban areas. This draws the attention to the influence of local urban characteristics on energy consumption that should be tackled with detailed study. Consequently, implementing strategies such as retrofitting and smart grid systems require an analysis of the specific characteristics of each urban area as land use mix, building typology, dwelling type, street geometry, and others, by local governments. These local characteristics or attributes are observed, for example, for the urban areas located in the Greater London region, which benefit from a better commute transport energy efficiency due to better public transportation system. In this way, the improvement of transport systems in other regions is expected to have significant impact on the reduction of carbon-based energy use.

Energy consumption is also affected by the land use typology observed by each area (which here can be considered the land use development stage, i.e. the urbanisation degree of a given area). By using more accurate boundaries of the urban areas produced by the cluster analysis, local governments or councils can apply distinct energy mitigation strategies depending on their different characteristics. This should follow, for example, compact city and urban sprawl theories, respectively, i.e. increase or decrease of density variables.

6.5.3 Determining urban boundaries

Defining the boundaries of urban areas is one of the major problems in planning, since administrative limits are often not accurate and boundaries change over time due to the continuous urbanisation (Tayyebi et al. 2011, Marcotullio et al. 2014). In this thesis, cluster analysis was used to identify land use typologies. These typologies can be an useful tool to define the urban boundaries as a large geographical scale (based on LSOA units) was applied.

Considering the obtained land use typologies and assuming the Local Authorities (LAs) boundaries as the limits of cities, Figure 6-1 shows that most of the Central region of Manchester is composed by already consolidated urban areas (essentially, Clusters 1 to 3). On the other hand, the South area is covered mainly by unconsolidated urban areas (mostly Clusters 4 and 5, but also some Clusters 3, 6 and 8). In contrast, Figure 6-2 for Croydon LA shows that the majority of consolidated urban areas (i.e. actual urbanized areas) are primarily located in the North area. These findings suggest that the city limits are not the boundaries defined by the LA. Furthermore, it indicates that energy-related reduction actions should be distinct for each LSOA unit.

Other examples (Figures 6-3 and 6-4) show that the urbanization level of Cambridge and

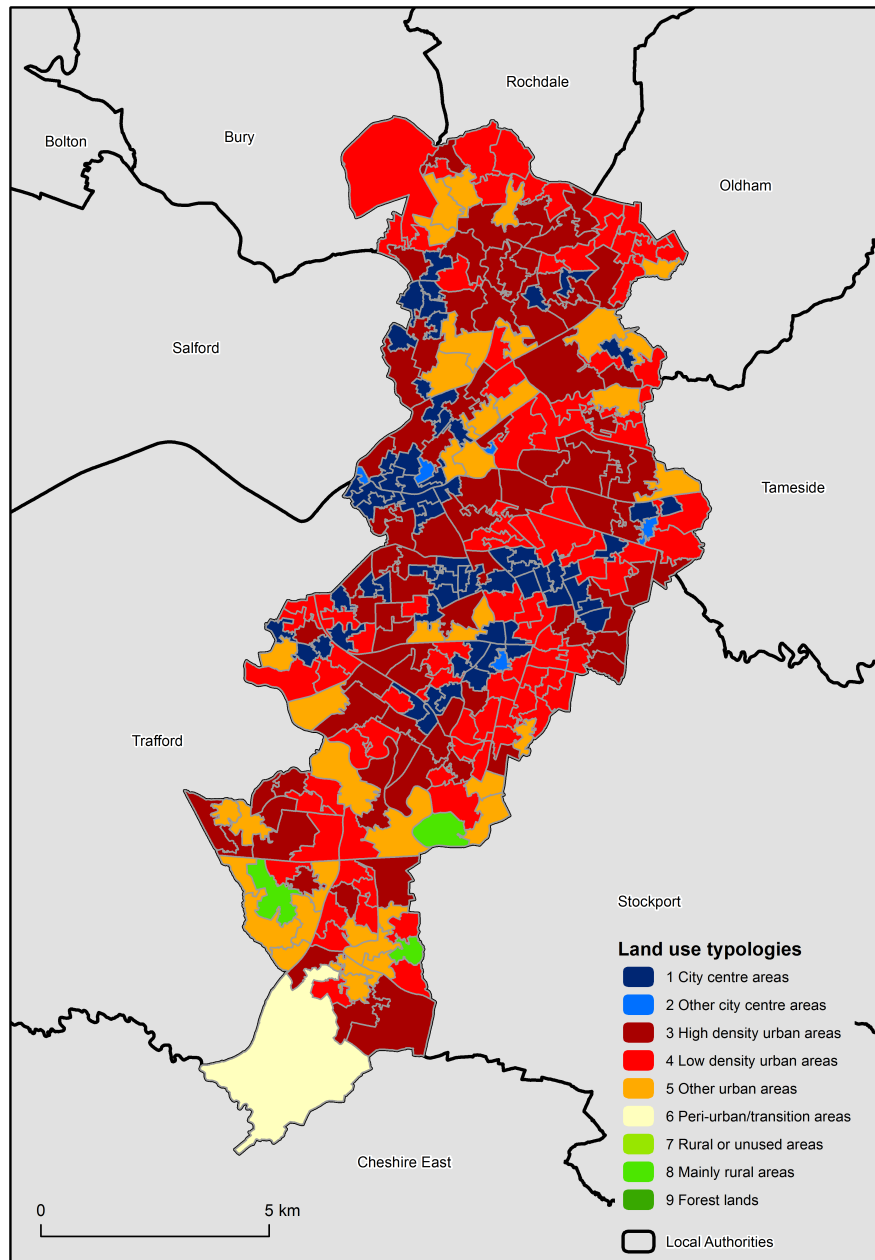


Figure 6-1: Land use typologies or clusters in the Manchester LA at LSOA level.

Oxford is different, the first with less consolidated urban areas than the second, although both polycentric cities due to the location of colleges throughout the LA. Mitigation strategies related to energy consumption in these cities should have a different framework planning to target distinct urban characteristics and consumption patterns. Nevertheless, considering that current urban planning does not ensure energy efficient cities (Amado et al. 2016), implementing policies and planning strategies such as imposing compact city or urban sprawl

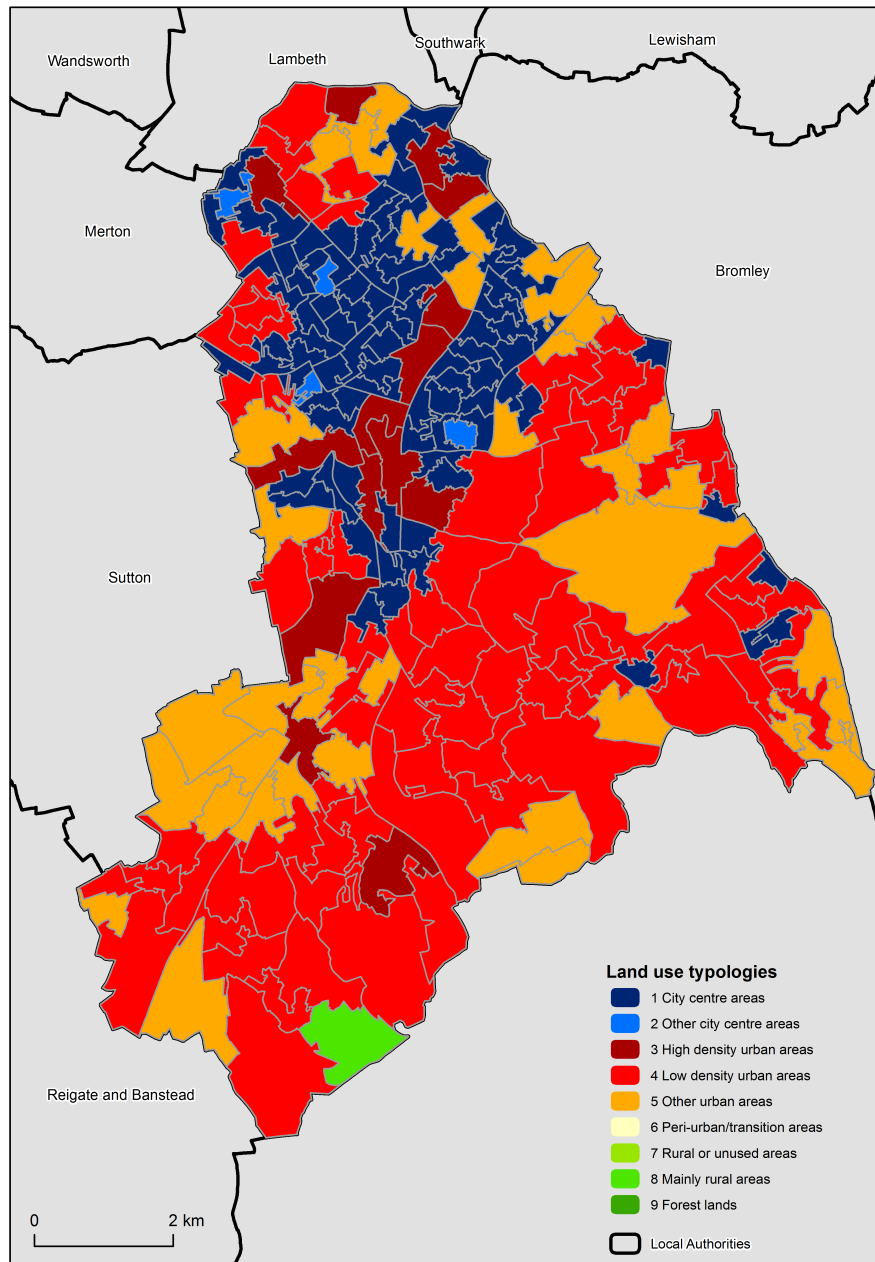


Figure 6-2: Land use typologies or clusters in the Croydon LA at LSOA level.

theories depends also from the political and economic systems and determination, especially at local and urban scales (Peck 2011, 2014).

Promoting urban sprawl seems to reduce the state authority at local scale in, for example, ethnically and/or social homogeneous suburban exclusive communities (Peck 2011, Ewing et al. 2016, Swyngedouw 2005). Furthermore, combining unregulated free-market

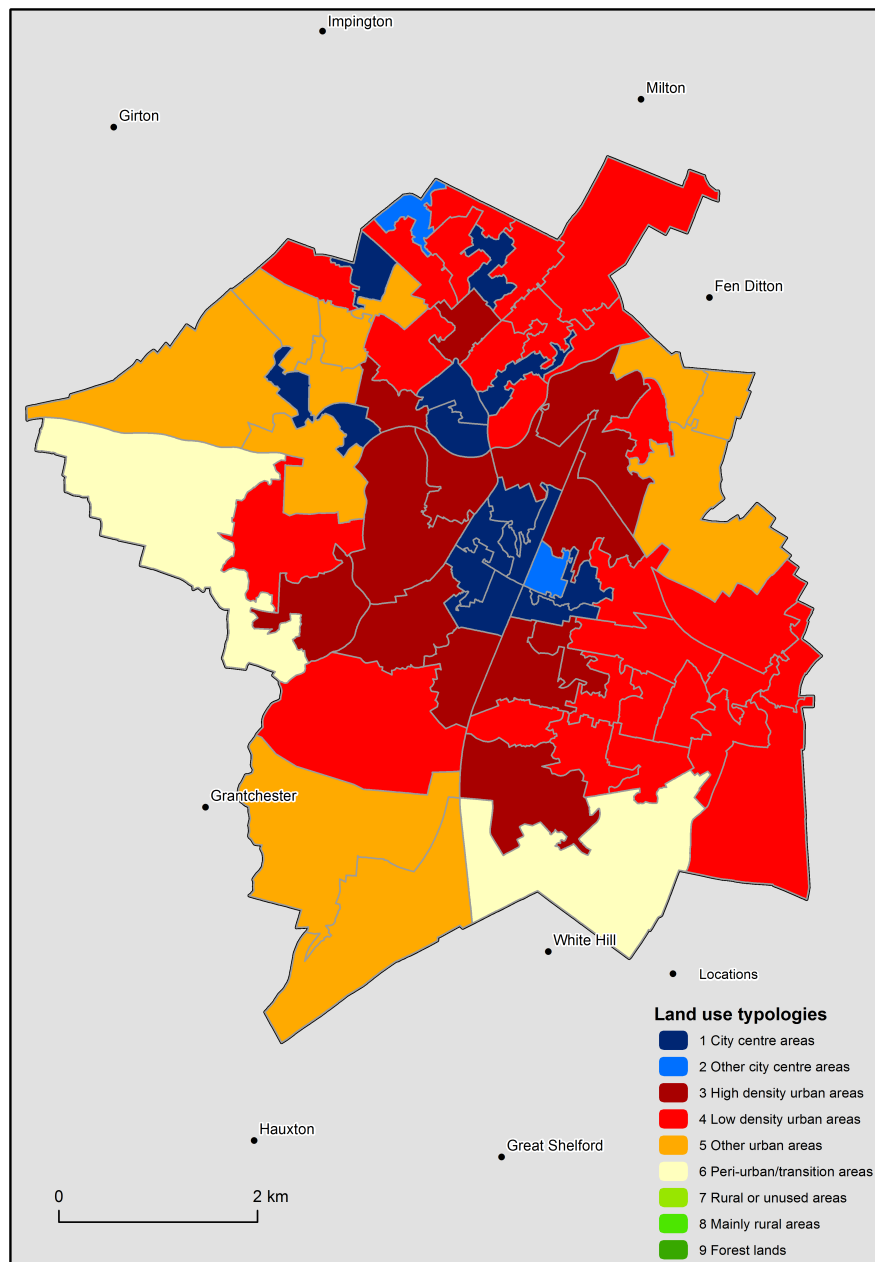


Figure 6-3: Land use typologies or clusters in the Cambridge LA at LSOA level.

neoliberalism and transferring state responsibility to the private sector and/or civil society usually leads the way to local authority government fragmentation (Peck 2011, Etherington & Jones 2016, Ekers et al. 2012, Neuman 2005). This fragmentation diminishes the capacity of local governments to impose and/or encourage changes and policies to the urban structure, geometry and characteristics, which may endanger the reduction goals of carbon-based energy consumption.

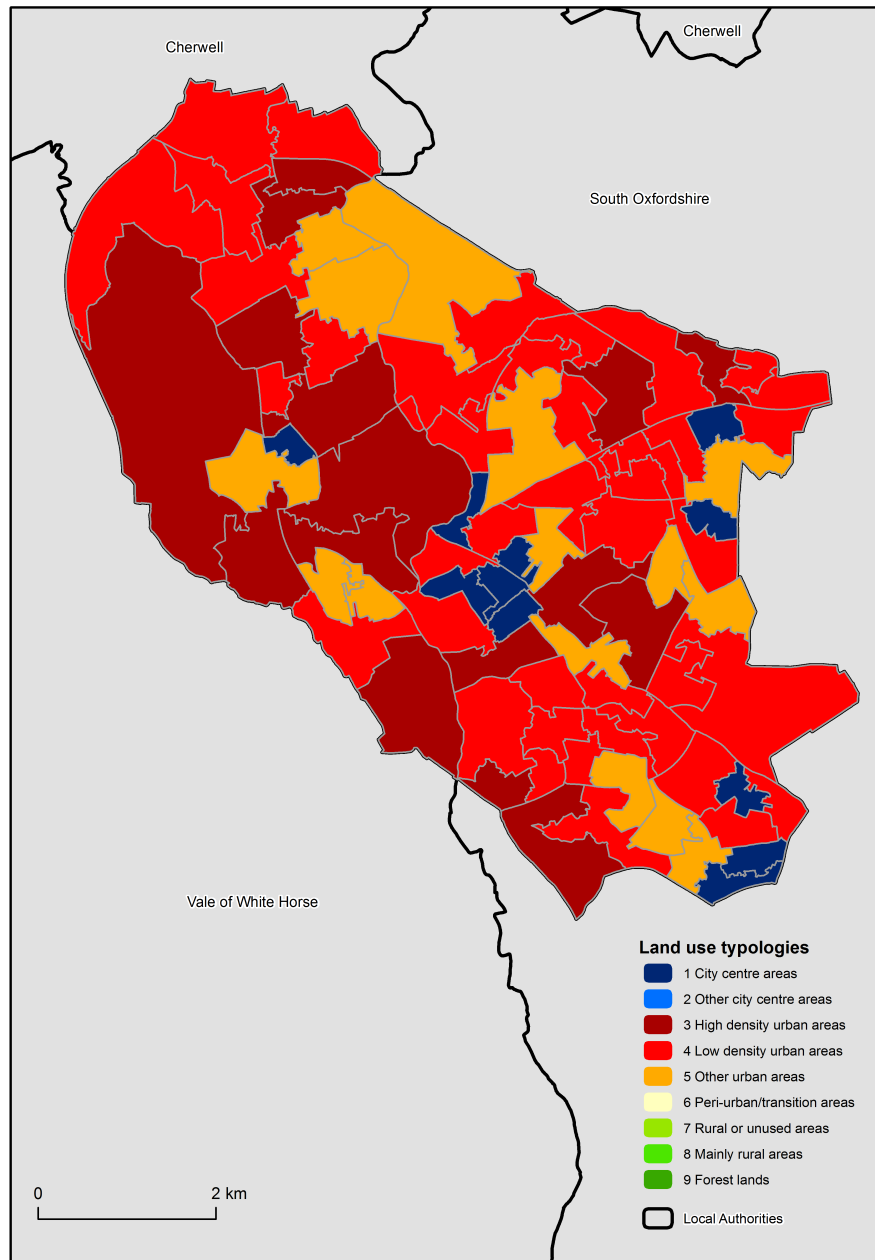


Figure 6-4: Land use typologies or clusters in the Oxford LA at LSOA level.

Additionally, the austerity urbanism process resulted in significant impacts of the neoliberal urban policies on cities, such as structural adjustment, privatisation and public-private partnerships (Peck 2014, 2012, Tabb 2014). This, in a way, weakened the authority of local governments to implement different urban planning actions. Therefore, the current negative outcomes in cities produced by an unregulated free-market observed in the West (but not limited to) appear to demonstrate the weakness of the liberal democratic political system

that is incapable of enforce local, regional and national policies that effectively reduce energy use. Can it be that only non-democratic societies (or practices) manage to outmanoeuvre these problems of private authoritarianism and sectorial lobbying to implement and apply policies that obtain a reduction of energy consumption and related impacts?

Recently, it has been observed special measures that restrict, for example, the access of vehicles (mostly private cars) to city centres such as Beijing and Madrid. In England, London has also imposed fees to the entry of private cars into the city. Although not directly linked with energy but the decrease of air pollution, these measures have an impact on the reduction of commute transport energy consumption. Even if non-democratic practices do not generate flawless results, they bring forth ways of opposing, for example, sectorial lobbying such as the car industry and the oil cartel business to achieve a more environmental and sustainable development that includes the mitigation or actual reduction of carbon-based energy use.

Chapter 7

Conclusions

The work presented here investigates the relationship between energy consumption and urban form based on readily available data at a large scale of analysis. Prompted by climate change and the need to mitigate the negative effects of carbon-related energy consumption, this research seeks to provide policymakers and planners with new knowledge about that relationship. This is achieved in three main stages: (i) defining a simple energy use metric; (ii) identifying land use typologies; and combining the results of both stages to (iii) investigate the relationship between energy and urban form by computing their correlation and scaling law exponents. A summary of the main findings and contributions of the research follows.

7.1 Summary, methodological contribution and findings

7.1.1 The new energy use metric

The better understanding of the relationship between energy consumption and urban form benefits, first, from a new, simple energy use metric (Chapter 4.1). The new metric integrates the operational energy consumption of buildings and commute transport. This approach integrates the main vectors over which it is expected for local authorities to have more direct control or influence. Furthermore, unlike many previous studies (Crawley et al. 2000, Howard et al. 2012, Heiple & Sailor 2008, Longhi 2015, Parshall et al. 2010, Travesset-Baro et al. 2016, Wang 2008), the energy metric uses a high resolution and is based on easily accessible data. This favours the replicability of the approach, an advantage also enabled by the simplicity of the method. Accordingly, the simplicity, the replicability

and the combination of buildings' and transport's energy use will to provide new knowledge and contribute to the development of the methodological approach of energy estimation. Additionally, the use of LSOA units as a large geographical scale can present planners and policymakers with new information about consumption patterns.

The application of the new energy metric shows that lower per capita energy consumption is found in the main cities and urban areas (Figure 5-7 on page 83). The largest consumption is found in most of the North region of England and the surrounding areas of the major urban spaces, generally rural/countryside areas. The analysis of the spatial distribution of energy consumption benefits from the use of LSOAs, enabling the identification of internal consumption dynamics within cities (here Local Authorities). The use of a large scale of analysis such as LSOA level is assumed to allow outlining more focused actions looking at reducing carbon-related energy demand. Moreover, the consumption patterns identified agree with the compact city theory that support an increase of population densities to achieve better energy efficiency (Newman & Kenworthy 1989, Næss 2012). Therefore, the results encourage the rise of density variables to counter the growth of energy use in cities.

7.1.2 Identification of land use typologies

The second stage of this work, preceding the study of the relationship between energy and urban form is the identification of land use typologies (section 5.2). This is based on a set of urban form variables and established by the use of cluster analysis. The use of urban form variables to define urban boundaries is expected to make a significant contribution to the literature, as one of the main problems of the study of urban areas is defining their limits (Masucci et al. 2015, Long 2016). Furthermore, considering that no definitive explanation of urban form exists (Schwarz 2010), the collection of a large dataset of urban variables provides support for future research. Covering a broader spectrum of urban form, this dataset includes variables related to physical, socio-economic and demographic characteristics of urban areas. Additionally, as with energy consumption, the use of LSOA units will allow the understanding of the internal and external development dynamics of cities by better identifying their consolidated and unconsolidated urban areas. The success of planning and policymaking depends much of this better knowledge of the territory.

7.1.2.1 The Principal Component Analysis

Prior to the application of cluster analysis, a Principal Component Analysis (PCA) was used to reduce the likely collinearity between the urban form variables (section 5.2.1). It was

found that the large compiled dataset can be explained by 6 main factors or dimensions (Table 5.1 on page 88). This brings into discussion the fact that, though no final definition of urban form is found in the literature, the concept may be described by a lower number of variables. Therefore, future studies on urban form may rely in fewer variables, as it will reduce the probability of collinearity, but also provide a sensible description illustration of cities and urban areas variables. It is assumed that similar results should be produced either using large or smaller datasets, as well as applying complex or simple procedures.

7.1.2.2 The cluster analysis

The cluster analysis in this work was carried out using two types of clustering: hierarchical and k-means. The results of the first type were used on the second, as this requires the definition of the number of clusters in advance. The procedure was supported by the analysis of the different outputs generated for the two types of clustering, allowing more reliable final results to characterize the land use in England. Previous research has applied cluster analysis to describe land use (Moreira et al. 2016, Zhou et al. 2014), but employing different approaches and data scales. Therefore, this thesis contributes to the ongoing debate on defining land use cover to support planning and policymaking. Moreover, the clustering procedure arises from a simple and easily replicable methodology that can be reproduced by local authorities or other end-users.

7.1.2.3 Findings

The analysis shows that the use of urban form variables generates relevant and meaningful land use typologies (section 5.2.3). The mapping of these typologies reveals a reliable characterization of the urban system in England (Figure 5-17). It is shown that land use is essentially split in: (i) major city areas (Clusters 1-2); (ii) surrounding high to low density urban areas (Clusters 3-5); (iii) transition areas (Cluster 6); (iv) predominantly rural/countryside to agricultural areas (Clusters 7-9).

The first group has fundamentally a consolidated urbanization where major businesses are conducted, including also the main historical centres of cities. This land use group is located on the more densely populated places that can be recognized in Figure 5-8 (see page 85). The second group include yet unconsolidated urban areas and is found surrounding the first land use batch. The following land use group (transition areas) acts as a buffer zone to urbanization, protecting rural areas. These buffer zones primarily create a ring surrounding the first two main land use groups and are located throughout England. Finally, the rural

areas are mostly situated in the North region, Cornwall and the remaining spaces not occupied by urban areas.

As with the energy use metric, the use of LSOA units allows the identification of the differences of land use within cities, as observed in Figures 6-1–6-4 on pages 142–145. It enables also the identification of the limits of urbanization at city and regional scale. This will provide new information to local and national governments about the location of the areas requiring immediate action regarding, for example, energy consumption mitigation. Therefore, the new information can be used to design actions supporting sustainable development, such as implementing strategies that reduce carbon-related energy dependency or that improve overall air quality. Overall, the detail level of LSOA brings insights of the geographical (physical) location of the different land use typologies that can be used to understand the urban system dynamics and the urbanization boundaries and phenomenon.

7.1.3 Using scaling laws and correlation

Ultimately, the relationship between energy consumption and urban form was studied using the results from the energy metric and the land use clusters. This was done by understanding the correlation and scaling laws dependencies between the two, and thus establishing the influence of urban form on energy. These are able to provide new perceptions about that relationship. Furthermore, the analysis in this work was carried out to different scales: land use typologies, selected Local Authorities (LAs), regions and the whole England by LSOA level.

7.1.3.1 Applying scaling laws: findings and recommendations

The use of scaling laws in this research expands its usage from the link between population and socio-economic variables in previous studies (Bettencourt et al. 2007, Gomez-Lievano et al. 2012) to examine energy consumption. The analysis was obtained at different scales, including land use clusters, selected LAs, regions and LSOA level (section 5.3.1). The results reveal a prevalence of sublinear scaling behaviour of the main urban form variables regarding energy (Figure 5-20), and thus complying with economies of scale. This agrees with the findings for correlation and indicates the conformity with the compact city theory by energy, i.e. more dense areas show lower energy consumption and thus better efficiency. Yet, the results also show that a significant number of urban variables do not follow a linear relationship with energy consumption. Additionally, the analysis by selected LAs and land use typologies demonstrate more relevant information, which follows.

The analysis shows a distinction between LAs located in the Greater London region and the LAs of the remaining regions (section 5.3.1.2). The sublinear scaling of the urban variables is prevalent for all LAs (Figure 5-23 on page 106), however the superlinear behaviour of some variables is found for LAs in Greater London. Considering that these superlinear scaling variables have significant impact on the increase of energy consumption, there is the need of implement actions to mitigate their influence on consumption. For instance, it is suggested that the proportion of population employed in services has an important effect on consumption in the City of Westminster. This is assumed as a consequence of the lower energy efficiency of non-residential buildings, thus calling for intervention on that matter to improve efficiency. In general, except for what is mentioned, it is not observed a major scaling behaviour tendency between LAs, as for example a difference between big and small LAs.

In contrast, significant dissimilarities are observed between land use clusters for the obtained scaling exponents (Figure 5-25 on page 109). These dissimilarities are mostly found between Clusters 1 & 2 and 3 & 4 (section 5.3.1.4), which illustrate the major city areas and surrounding urban areas, respectively. The differences fundamentally refer to density variables by showing that the increase of, for example, population density in already densely populated areas (as Clusters 1 & 2) is not meaningful to lower energy consumption, in opposition to what is found by yet unconsolidated or suburban-like areas (such as Clusters 3 & 4). However, despite these distinctions the scaling relationship between energy consumption and the urban form variables at land use typology or cluster level show a prevalence of sublinear scaling behaviour. Therefore, the impact on consumption of the growth or decrease of those variables is not significant.

Power-law scaling analysis also shows that socio-economic variables have more effect on energy consumption due to their higher exponent values. This differs from urban sprawl principles that proclaim a bigger impact of infrastructures on energy. Consequently, policy-making and planning should target these socio-economic variables to reduce energy demand in urban areas. Furthermore, the scaling variance between land use typologies demonstrates the relevance of understand the development phase of urban areas before proposing and implementing strategies.

7.1.3.2 Applying correlations: findings and recommendations

The analysis of the correlations (section 5.3.2) show, essentially, moderate strengths to much of the density variables (such as population density) and size-related variables (such as total surface area), with a negative and positive tendency, respectively, in relation to

energy consumption (Figure 5-32 on page 120). These results support the compact city theory expressing lower energy consumption by higher density areas. However, relevant differences were identified between land use typologies, selected LAs and the whole LSOA dataset.

It is observed two trends for the relation between energy and population density (Figure 5-27 in section 5.3.2.1). These trends demonstrate that the individual physical and socio-economic characteristics of the LSOA units have significant impact on energy consumption and efficiency, as one of the trends favours efficiency and the other results in bigger consumption growth when, for example, population density increases. Further analysis (Figure 5-28 in section 5.3.2.4) indicate that those characteristics of the LSOAs are, essentially, related to buildings, since the two trends are still identified for the relationship between density variables and energy consumption of buildings alone.

The results for the regional analysis (Figure 5-29 on page 115) and the identification of two different correlation trends also suggest that the impact of density on energy consumption is not uniform all over England. The Greater London region is a special case due to the centralization of people and business activities. This centralization plays an important role in the energy efficiency of LSOA units at regional level, as the correlation analysis shows that more densely populated areas have lower energy consumption (thus are more efficient). On the other hand, the analysis of selected LAs does not reveal a tendency: multiple correlation trends are shared by both historical and new LAs, as well as large and small LAs (Figures 5-30, 5-31 and 5-35 on pages 117, 118 and 123). The almost unique identified trend for these LAs is the stronger correlation established between the energy of buildings and urban variables than transport energy. This shows the lower energy efficiency of commute transport.

The findings of the correlations between energy consumption and urban form variables established for the land use typologies are more significant (Figure 5-36 in section 5.3.2.6). It is demonstrated that the compact city assumptions to increase population densities to achieve better energy efficiency may be unmeaningful and have no real impact for already consolidated urban areas (such as Clusters 1-2 and, in a lower scale, Cluster 3). This means that energy consumption will not decrease significantly in these areas if population density increases. However, for suburban-like areas (such as Clusters 4-5, but also overall in Cluster 3), it is expected that energy consumption decreases with the rise of density variables as population density. This outcome partially disagrees with urban sprawl theories (Ewing 2008, Brody 2013) claiming an increase of energy consumption with suburbanization. The areas of Clusters 4-5, clearly still undergoing an urbanization process, can improve yet their energy efficiency (and so decrease consumption overall) by increasing the value of density

variables, such as population density.

Further findings show that the effects of, for example, variables such as the green space and the area of buildings on energy consumption are insignificant, given the weak correlation values obtained for nearly all land use clusters. The weak correlation coefficients obtained for green space or area have important meaning to planning theories, because it has been considered that increasing green area would produce lower energy consumption. From the analysis in this thesis, that assumption is not confirmed for the whole LSOA dataset by land use clusters or typologies (Figure 5-36 on page 125).

Altogether, the different correlation values of the relationship between energy and urban form found for each cluster demonstrate the pertinence of studying that relationship at distinct scales. This also shows the importance of analysing beforehand the local characteristics of the target locations, such as the land use development, by planners and policymakers prior to outlining and implementing policies and actions (Moghaddam et al. 2014, Østergaard & Sperling 2014, Pasimeni et al. 2014).

7.2 Final conclusion and contributions to planning

The main aim of the research developed in this thesis concerns the relationship between energy consumption and urban form variables. Based on the application of correlation and scaling laws analyses, new insights were found about that relationship and how one set influences the other. The work also delivers new knowledge related to energy consumption patterns throughout England, as well as brings forth a novel understanding of the land use in the country. On the whole, the methodological procedure followed in this research shows:

1. convenience of using official governmental datasets or sources by end-user or local councils;
2. reliability and accessibility of official sources benefits their research usage;
3. consistency of results by applying the same geographical unit (LSOA) for the different analyses;
4. relevance of applying a large geographical scale to focus policies;
5. replicability of the methodology favoured by the non-complex approach;
6. practicality of the downscaling technique to overcome the problem of using data at different geographical resolutions;

7. feasibility of a simple, new energy use metric combining the energy consumption of buildings and transport;
8. efficiency of cluster analysis to identify land use typologies;
9. benefit of employing automated Python or R scripting processes to large datasets.

As aforementioned, the results also bring new insights about the relationship between energy and urban variables. Furthermore, the outcomes of the energy use metric and the analysis of the land use typologies reveal the contrast among the different regions and LAs in England. Comprehensively, the overall results of the thesis demonstrate:

1. predominant sublinear scaling behaviour of most of the urban variables regarding energy consumption, essentially showing that consumption follows an economy of scale;
2. prevalent moderate to weak correlation strength of the variables with energy;
3. more significant influence of socio-economic variables on consumption than physical variables;
4. stronger correlation is found for density and size variables than the remaining, and more with commute transport energy consumption than buildings;
5. support for the compact city theory due to the results from the correlation and scaling laws analyses, but also from the per capita energy consumption maps;
6. distinction of correlation values and scaling behaviours among the land use typologies, but mainly between urban and transition/rural areas;
7. significant effect of the proportion of population employed in services on energy consumption of highly urbanised places, such as the City of Westminster;
8. important dissimilarity of results between Greater London and the remaining regions in England, illustrating how distinct that region is from the rest of the country;
9. contrasting per capita energy consumption patterns between the large consuming North region of England (here considered most of the counties of Northumberland, Cumbria, North Yorkshire and North Lincolnshire) and the lower consumption by the main LAs and urban areas, and so more energy efficient;
10. similarity between total per capita energy consumption and building consumption only;

11. four major land use typologies groups can describe the urban system in England: (i) main city and urban areas; (ii) suburban areas; (iii) essentially transition spaces; (iv) rural or agricultural area;
12. a satisfactory definition of urban form can be described by a smaller number of variables and, to a large extent, by six main factors or dimensions referring to area size, built-up area, density of housing, housing, socio-economic status and population;
13. more than 40% of England's total surface area is occupied by rural/unused areas and forest lands, contrasting with the less than 20% covered by cities and general urban areas.

The results from this work provide new information about the relationship between energy and urban characteristics that can be used by policymakers and planners to outline more focused and detailed actions to mitigate energy use in England. These actions are regarded as derived from the results of the research and include:

1. favour the increase of density variables, such as population density, in yet unconsolidated areas (mainly associated with land use Clusters 3 and 4) to improve energy efficiency;
2. prevent the application of compact city theory of expanding densities in already highly urbanised areas, such as land use Clusters 1 and 2;
3. recommend the economy of scale to socio-economic urban variables as these have a more significant effect on energy consumption;
4. support an improvement of the public transportation system to achieve a better energy efficiency, mimicking the efficient system set up in the Greater London region;
5. preserve the transition land use areas (mostly Cluster 5) to avoid the encroachment of rural areas;
6. promote more environmental friendly behaviours as these are not observed at LSOA level, not even for individuals with higher education;
7. improve the energy efficiency of non-residential buildings located in already consolidated urban areas due to the important impact on energy consumption;
8. benefit the enhancement of per capita energy efficiency in the North region of England through measures applied directly to buildings efficiency given the large energy consumption observed in the region;

9. direct energy mitigation strategies at an appropriate geographical scale since the results show distinct effect by each urban form variable;
10. analyse the different urbanisation development stages beforehand to identify the urban boundaries within LAs and target better policies considering the distinct characteristics of each area, as for example to promote competitive city centre environments as mentioned in the NPPF (DCLG 2012).

7.3 Future work

The research presented here provides new contributions to knowledge, mainly about the relationship between energy and urban form at a large geographical scale. The results also raise important questions about that relationship, for example related to the urban development theories and energy costs associated with each one. It is therefore hoped that the work can be used as tool for urban planning and policymaking. At the same time, it is expected that further research follows from the obtained outcomes and the methodological approach. The concluding remarks in this section are intended to provide general framework guidance for future research, though not imposing limits on future analyses. The following would benefit from the work developed in this thesis:

1. development of 'what if' scenarios based on the results of the energy use metric, considering the prospective growth of population and respective increase of energy demand. Localised scenarios can help to understand the variation of important physical and socio-demographic urban variables to anticipate impacts and put forward strategies and policies that mitigate them. For example, the 'return to the city' phenomenon and the increase of intra-urban migration between the 2001 and 2011 Censuses (Rae 2013, Lomax et al. 2014) produced population growths in major cities of England, to which social and health support schemes were not prepared and thus resulting in the increase of urban deprivation (Rae 2013). A better prediction of energy demands at large scale would provide local governments with valuable information to anticipate impacts;
2. application of the energy metric to Scotland, Wales and Northern Ireland to quantify energy consumption needs at UK level, but also at local scale. Furthermore, the methodology can also be applied to other countries if the LSOA-alike units are available, as well as buildings and commute transport energy consumption datasets;
3. expand the study of power-laws scaling to more LAs to identify possible patterns

between urban areas. This can provide new knowledge about the relationship between energy consumption and urban form variables that can be used to inform policymakers and planners seeking to reduce carbon-related energy consumption;

4. expand also on the correlation analysis to better understand which local characteristics have more impact on energy consumption;
5. further study the implications of the land use clusters to redefine the boundaries of cities and general urban areas. This better redefinition of boundaries will allow the application of more focused strategies to reduce consumption, as it will be based on the characteristics of each land use typology or cluster.

7.4 General summary

The research work presented in this thesis delivers new knowledge about the relationship between energy consumption and urban form variables at different scales. In general, it is found a prevalent sublinear scaling behaviour between the two datasets, thus abiding by economies of scale, i.e. a lower impact on energy with the increase of urban variables such as population density. This demonstrates a better energy efficiency with the growth of, for example, population or density in a given urban area, and the observation of compact city theory.

The analysis of the scaling relationships also showed that the geographical location of LAs has an influence on their energy consumption, since differences were observed between LAs in the Greater London region and the remaining regions. These differences demonstrate the importance of localized planning and policymaking, depending of the local characteristics to expect better results.

Furthermore, at land use typology level it was observed significant dissimilarities between consolidated and unconsolidated urban areas. These dissimilarities show, essentially, that different urban variables have an impact on energy consumption, according to the land use typology or cluster. The analysis also demonstrated that socio-economic variables have more impact on consumption than other variables. This finding is relevant for planners and policymakers that can focus strategies on those variables to mitigate or reduce energy consumption in urban areas.

Additional findings are related to the correlation analysis. For the whole LSOA dataset, it was found that more densely populated areas are more energy efficient, and thus complying with the compact city theory. The Greater London region is the best example of this, as it

shows lower energy consumption in higher population density areas (LSOAs). However, the comparison at LA level does not demonstrate any correlation tendency for the relationship between energy and urban form variables. Therefore, the contrast between LAs is not explained by the selected urban variables.

Other results at land use level show that the compact city theory, i.e. the increase of density variables to obtain better energy efficiency, is not observed for already densely populated clusters. Only for suburban-like clusters, the increase of density is expected to have an impact. Overall, the distinct correlation and scaling exponents obtained at different geographical scales indicate the importance of analysing energy consumption at specific scales to be able to design policymaking and planning with better rate of success.

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